Appendix F—Belvidere Area Data

The USGS and USEPA began to perform detailed investigations of the Galena-Platteville aquifer in the Belvidere area during 1990 with the first of six investigations at the PCHSS. Prior to the studies by the USGS and USEPA, hydrogeologic data pertaining to the Galena-Platteville aquifer in the Belvidere area were limited to less than 20 lithologic logs and monitoring wells installed in the upper 30 ft of the aquifer. These data were collected as part of IEPA-coordinated studies of three Superfund sites. The investigations performed at the PCHSS indicated the need for an area-wide understanding of ground-water flow and water quality in the bedrock aquifers, particularly the Galena-Platteville aquifer. Therefore, investigations of hydrogeology and water quality in the greater Belvidere area were performed. The various USGS and USEPA investigations in the Belvidere area and at the PCHSSS were completed by 2002.

Data that form the primary basis for this discussion were collected throughout the Belvidere area; however, borehole and monitoring-well data are concentrated within the city of Belvidere, and particularly in the vicinity of the PCHSS (figs. 30, 31; tables 17, 18). Details of the Belvidere area investigations, including investigative methods and results, are presented in Brown and Mills (1995), vanderPool and Yeskis (1991), Mills and others (1998, 1999b, 2002a, b), and Mills and Kay (2003). Details of the USGS and USEPA investigations focusing on the PCHSS are presented in Mills (1993a, b, c), Mills and others (1994, 1998, 1999a), Kay and others (2000), and Kay (2001).

Previous Studies and Database Search

Various hydrogeologic studies of the Galena-Platteville aquifer have been done in the Belvidere area, including studies of three Superfund sites (Roy F. Weston, Inc., 1988; Science Applications International Corporation, 1992, 1996, 1998; Clayton Environmental Consultants, 1996), an industrial facility (GZAGeoEnvironmental, Inc., 1993), one leaking underground-storage-tank site (Total Environmental Services, 1992) and a multi-county study (Berg and others, 1984). With the exception of the study at the industrial facility, hydrologic data from the Galena-Platteville aquifer collected by previous investigators were sparse and limited to the upper 30 ft of the aquifer. The previous studies expanded the distribution of hydrologic data and provided a preliminary hydrogeologic and water-quality framework for the Galena-Platteville aquifer.

A detailed study of the stratigraphy and lithology of the Galena and Platteville Groups throughout their subcrop area by Willman and Kolata (1978) particularly was useful in initial characterization of these units and features of the units that possibly affect ground-water flow and contaminant migration. Detailed studies of the distribution and orientation of orthogonally related fractures in the Galena and Platteville Groups, where exposed in outcrops and quarries in northern Illinois (Foote, 1982; McGarry, 2000), were useful in initial characterization of aquifer anisotropy and possible preferential flow paths. These studies indicated primary and secondary orientations of the fracture sets of about N. 60-75° W. and N. 30° E., with variability in the orientation of fracture sets.

A survey was done to identify existing wells and test borings within the Belvidere area (Brown and Mills, 1995). The survey included retrievals from the well-construction databases maintained by the USGS and the ISGS and data from reports on the environmental studies at the three Superfund sites, leaking underground-storage-tank sites, and other hazardous-waste or industrial sites in the area. From this survey, 725 wells and borings were identified, including 380 open exclusively to the Galena-Platteville aquifer. Lithologic logs available for these wells were used to determine the lithology, distribution, and thickness of the unconsolidated and bedrock deposits in the Belvidere area. These logs rarely were detailed enough to assist in the identification of stratigraphic subunits or permeable intervals associated with fractures or other features.

Quarry and Outcrop Visits

Hydrogeologic features were mapped and ground-water discharges and withdrawals were identified during inspections of the Schlicting, Irene Road, and Belstone Quarries in the Belvidere area (table 17)(fig. 30). Limited solution was observed at fractures and bedding-plane partings and water seepage was observed above low-permeability intervals in the Galena Group at the Irene Road Quarry. One particular interval restricting flow was identified as the Dygerts bentonite bed in the Wise Lake Formation. This bed was not detected in other parts of the Belvidere area, nor was this interval associated with ground-water flow.

Vertical-fracture orientations of a representative fracture set in the dolomite were measured at an unnamed quarry in the northwest part of the study area (fig. 30). The primary and secondary orientations of N. 80° W. and N. 10° E. varied by about 20° from the orientations mapped by Foote (1982) and McGarry (2000) in nearby quarries (N. 60° W. and N. 30° E), but were within their range of measurements.

A unit tentatively identified as belonging to the Dubuque Formation is exposed at a natural outcrop adjacent to the Belstone Quarry (Dennis Kolata, Illinois State

Geological Survey, oral commun., 1995). The Dubuque and Wise Lake Formations both were identified at the Irene Road Quarry.

Quarry inspections enhanced understanding of the stratigraphy and lithology of the Galena-Platteville deposits, orientation of some of the secondary-permeability features in the dolomite, and some of the hydrogeologic features that affect ground-water flow.

Surface geophysics

Azimuthal square-array direct-current resistivity (SAR) surveys were done at the PCHSS and at two sites located along the southernmost of the northeast-trending bedrock highs near the Irene Road Quarry and near Stone Quarry Road (table 17, fig. 30) (Mills and others, 1998). At each site, up to nine surveys were conducted representing increasingly larger squares (from about 14 to 223 ft), and, theoretically, detection and measurement of orientation of increasingly deeper fractures.

The SAR survey done at the PCHSS indicated two or more fracture orientations along each square, which the orientations varying by as much as 60° between squares. The primary orientation of the inclined fractures indicated by the SAR data for the smallest squares (25, 36 and 42 ft) was N. 90° E. The primary orientation of the inclined fractures indicated by the SAR data for the two largest squares (110 and 160 ft), those least likely to be affected by the overburden, was N. 45° E. with a secondary set oriented at about S. 45° E. A secondary porosity of about 15 percent was estimated with the SAR data from the squares less than 110 ft in size, but could not be calculated from larger squares. The SAR survey at the PCHSS was affected by substantial cultural interference including high-power, electrical-transmission lines, and underground metal piping. Because of the interference, survey results were considered unusable.

Deeply penetrating high-angle fractures (interpreted as extending to about 223 ft below land surface) tentatively were identified at the Stone Quarry Road and Irene Road sites. The survey at the Stone Quarry Road site indicated primary and secondary orientations of this deep fracture set of about N. 60° E. and N. 45° W., respectively. The survey at the Irene Road site indicated a primary orientation of the deep fracture set of about N. 30° W. (fig. A2). A secondary porosity of typically less than 1 percent, and decreasing with depth, was calculated at these sites. Variability in the results indicated the possibility of nearby electrical interference (Peter Joesten, U.S. Geological Survey, written commun., 1996); however, the closest identified above-ground power lines were about 700 ft from the sites. Operations at the quarry adjacent to the Irene Road site may account for the difference between fracture orientations at the Irene Road and Stone Quarry Road sites.

The SAR surveys, although providing information on porosity and fracture orientation, are not necessarily considered to be reliable because of the effects of cultural interference. This unreliability is indicated by differences in fracture orientations with depth at each site and between sites, coupled with poor-to-moderate agreement with orientations determined by previous investigations, quarry visits, and borehole-geophysical methods. The surveys appear to verify the presence of orthogonal fracture sets in the Galena and Platteville Groups.

Lithologic Logs

Lithology and substantial changes in water return during drilling were described for all of the boreholes drilled by the USGS for investigations in the Belvidere area, particularly those in the vicinity of the PCHSS (tables 17, 18, 19). For this investigation, a BMW prefix in the location identifier denotes a Belvidere Municipal Well. A B or T prefix in the location identifier denotes that the activity was performed while the location was a borehole. A G prefix in the location identifier denotes that the activity was performed in the monitoring well completed in that borehole. USGS drilling logs provided preliminary information on the location and distribution of secondary-permeability features in the dolomite. This information generally was confirmed and expanded upon during subsequent data collection. Fractures were indicated at borehole T4 at the PCHSS between 734 and 739 FANGVD29 and at about 742-744 FANGVD29 in boreholes T5-T8 at the PCHSS (table 19). With the exception of an apparent fracture at about 709 FANGVD29 in boreholes T1 and T2 (table 19), fractures or solution openings in the deeper part of the aquifer were not identified with lithologic logging.

All boreholes described here returned moderate to large volumes of water during drilling, indicating generally permeable rock, with that part of the boreholes near the bedrock surface tending to be the most permeable. For example, borehole T4 at the PCHSS indicated a loss of circulation during drilling between 734 and 739 FANGVD29, and increases in water return were observed at about 742-744 FANGVD29 in boreholes T5-T8, indicating the presence of a permeable feature at these altitudes (table 20). With the exception of an increase in water return at about 709 FANGVD29 in boreholes T1 and T2, clear indicators of permeable features in the deeper parts of the aquifer were not readily apparent during drilling.

Core Analysis

Cores collected from overlapping altitudes in boreholes B115BD, B125B, B126BD, B127GP, B127SP, and B128GD were described to provide a composite of the stratigraphy in the vicinity of the PCHSS (Michael Sargent, Illinois State Geological Survey, written comun., 1992; Mills and others, 1998)(table 17, fig. 31). These core data are assumed to typify the Belvidere area.

The cores indicate that the Platteville and Galena Groups are composed of the Pecatonica (about 451-478 FANGVD29), Mifflin (about 478-501 FANGVD29), Grand Detour (about 501-547 FANGVD29), Nachusa (about 547-556 FANGVD29), Quimbys Mill (about 556-568 FANGVD29), Dunleith (568-633 FANGVD29), and Wise Lake and Dubuque Formations (633 FANGVD29 to the top of bedrock) (fig. 35). The contact between the Wise Lake and Dubuque Formations could not be differentiated in the cores and the two units are not differentiated. An unconformity is present in the dolomite between the Quimbys Mill and Dunleith Formations at about 568 FANGVD29.

Differentiation of the formations (and to a greater extent, members) that compose the Galena and Platteville Groups from the cores proved difficult, because traditional differentiation is made primarily on the basis of the weathering signature of exposed units. Subsequent use of natural-gamma logs assisted differentiation of the units by allowing identification of variations in clay content. However, stratigraphic delineations made on this basis of natural-gamma signatures can be inconsistent with those made on the basis of weathering signature. Error in the identified depths of stratigraphic transitions between some units that are similar in lithology, particularly within the Galena Group, may be as much +/- 25 ft. The difficulty in delineating the stratigraphy of the Galena Group is compounded by possible erosion or removal of bentonite marker beds during drilling. In particular, what has been identified as the Dygerts bentonite bed (Willman and Kolata, 1978; McGarry, 2000) at the Irene Road Quarry (fig. 30) does not seem to be present where cores were collected.

Core analyses indicate the Galena and Platteville Groups are composed of dolomite; no limestone was identified during inspection. The argillaceous content of each Group varies, with the Platteville Group being more argillaceous than the Galena Group. The highest percentage of clays are indicated in the Mifflin Formation, with as much as 15 percent of the 25-ft section of core consisted of shale interbeds, most less than 2 in. thick.

Vuggy porosity generally is developed in units with low clay content (fig. 35). Core inspection indicated vugs are best developed in the Galena Group and in the Nachusa Formation of the Platteville Group. Vuggy intervals in the cores seem to be best developed at about 550-660 FANGVD29 (at about 125-235 ft below land surface). Visual inspection of the cores provides no indication that the vugs are highly interconnected.

Prominent inclined fractures were not identified in the cores. Weakly developed healed fractures are present at many intervals within the Galena Group, but virtually are absent within the Platteville Group, indicating that the density of the inclined fractures decreases with depth. Numerous horizontal breaks are described in the cores, generally along shale partings. No weathering was identified along the breaks and they are attributed to mechanical breakage during core collection. With one possible exception, no pronounced intervals of solution associated with the partings or other horizontal bedding features were detected in the cores. A gravely mud is described as “sticking” to the core collected from borehole B128GP at an altitude of about 530 ft (depth about 250 ft) (Mills and others, 1998). The origin of the mud is uncertain and is described as possibly (1) a potassium-bentonite clay bed, (2) a mud-filled fracture, or (3) mud from the drill site.

The primary porosity of the Platteville and Galena Groups determined from 57 core samples ranged from about 4 to 25 percent with a geometric mean value of about 9.6 percent (fig. 35)(Mills and others, 1998). The geometric mean value for primary porosity was 5.1 percent for the Mifflin Formation, 6.6 percent for the Grand Detour Formation, 7.4 percent for the Quimbys Mill Formation, 8.3 percent for the Pecatonica Formation, about 12.1 percent for the Dunleith and Dubuque/Wise Lake Formations, and 12.6 percent for the Nachusa Formation. The primary porosity of the core samples from the Dubuque and Wise Lake Formations (the uppermost units in the area) is consistent with the secondary porosity of about 15 percent calculated with the SAR survey at the PCHSS.

Laboratory porosity estimates provided better understanding of the effective primary porosity of individual stratigraphic units than visual core inspection. Intervals of the Galena and Platteville Groups with comparatively high porosities generally coincided with intervals identified as vuggy by acoustic-televiewer logging and, in some cases, with flow, as measured with the flowmeter. The core analyses provided no hydraulic information about bedding-plane partings or fractures.

In general, analysis of cores provided useful information on lithology, stratigraphy, and matrix characteristics such as primary porosity, and, perhaps, trends in density of fractures in the Belvidere area. Core analysis was less useful in identification and description of fractures and solution zones. Possible error in depth identification also may be associated with core analysis, as the result of mechanical breakage and partial core recoveries.

Geophysical Logs

Various geophysical logs were run in boreholes and wells open to the Galena-Platteville aquifer in the Belvidere area (table 17). The boreholes were distributed across an area of about 1.5 mi^2 in Belvidere, concentrated in the vicinity of the PCHSS. Many of the log types were useful in enhancing characterization of the hydrogeologic framework of the Galena-Platteville deposits underlying the Belvidere area.

Borehole Camera

Camera logging was done in seven boreholes and one well (table 17), six with a side-looking, black-and-white camera and two (BMW2, B128GP) with a color camera using down- and side-looking lenses. Logging with the black-and-white camera was limited by cable length to a depth of 120 ft. Logging of borehole B305 was limited to inspection of a well obstruction because the camera could not be adequately focused in the 10-in. diameter well; most boreholes were 6 in. in diameter. Water clarity in the boreholes typically was adequate for camera logging.

Various observations specific to individual boreholes were made during camera logging. Bedding-plane partings were identified at altitudes of about 660 and 525 FANGVD29 (referred to in previous reports as the 125-ft and 260-ft partings on the basis of depth at the PCHSS and referred to as the 660-ft and 525-ft partings in this report) in borehole B128GP (table F1, fig. 35). On the basis of the camera log from this borehole, the aperture of the 525-ft parting is estimated at about 2 in. This altitude is about 5 ft lower than the location of the gravelly mud is described in the core collected from borehole B128GP, indicating either that this is not the same feature or that the core depth was inaccurate because of breakage. Although no fracture was identified at this altitude, material suspended in the water column was observed moving out of borehole B128GP and into the aquifer at about 485 FANGVD29, indicating the presence of a permeable feature.

The 660-ft parting was identified in borehole B436GPD (fig. 30, table F1). The water in this borehole was turbid at about 685 to 675 FANGVD29. The turbidity could not be attributed to any features noted in camera logging, however, water clarity improved at 675 FANGVD29, possibly indicating a permeable fracture at this altitude.

The 660-ft parting and an inclined fracture at an altitude of about 630 FANGVD29 were identified in municipal well BMW2 (fig. 30, table F1). Although vertical offset across the wall of the well was noted, the dip angle was not quantified. The aperture of the fracture is estimated at about 1 in. Camera logging indicated that many of the enlargements in the well that appeared to be fractures or partings in geophysical logs, were the effects of drilling—that is, change in the size of the drill bit or off-center movement of the bit. The distinct transition from dolomite of the Platteville Group to the sand-rich deposits of the underlying Glenwood Formation and St. Peter Sandstone were identified readily in the camera log.

Vugs were identifiable in all of the camera-logged boreholes; vuggy intervals were recorded that generally correlate with intervals identified in rock cores. Bedding-plane partings and inclined fractures with apertures greater than about 0.5 in. generally were identifiable. Many of the smaller partings identified with camera logs were not identified in the borehole-geophysical logs. Bedding-plane partings and fractures were identified readily in the wells logged with the color camera; the depths of most of these features were greater than the cable length of the black-and-white camera. Cavities immediately below the casings of boreholes B115BD and B126BD also were identified readily. The cavities indicate that the boreholes may not have been cased adequately into the competent deposits below the weathered-bedrock surface. Images with the best resolution were obtained using the black-and-white camera. For the color camera, images from

Table F1. Principal bedding-plane partings identified in the units that compose the Galena and Platteville groups underlying Belvidere, Ill.

Approximate altitude of parting (feet above National Geodetic Vertical Datum of 1929)	Formation where parting was identified	Borehole or well where parting was identified
740	Dubuque/Wise Lake	BMW2, B115BD, B124GP, B125BD, B126BD, B128GP, B126GP, T5, T6, T7, T8
660	Dubuque/Wise Lake	T1, T2, T3, T4, T5, T6, T7, T8, B305SP, BMW2, B124GP, B126GP, B128GP, B130GP, B133GP, B134GP, B136GP, B436GBD
590	Dunleith	B305SP, BMW2, B128GP,
560	Quimbys Mill	B124GP, B128GP, B130GP
525	Grand Detour	B305SP, B124GP, B126BD, B127GP, B128GP, B133GP, B136GP, G137GP
485	Mifflin	B128GP, BMW2

the downward-looking lens had better resolution than images from the side-looking lens. Major changes in lithology (such as from dolomite to sandstone), but not particular lithologies, were identified with both cameras. Changes in lithology were indicated by changes in the intensity of light reflected from the borehole wall and changes in rock color. Both cameras provided depth measurements accurate to about +/- 1 ft. Differences in depths measured with the cameras and other geophysical-logging tools had to be accounted for when comparing identified features; in some cases, these differences seemed as large as 5 ft.

Caliper

Three-arm caliper logging was done in 21 boreholes and 1 well (table 17). Caliper logs indicate increases in borehole diameter of more than 1 in. at about 525, 563, 595, and 660 FANGVD29 in borehole B128GP (fig. F1, table 19); 660 FANGVD29 in borehole B436; 742 FANGVD29 in boreholes T6 (fig. F2, table 19) and T8; at about 525 FANGVD29 in borehole B127GP (table 19, fig. F3), and immediately below the casing at about 747, 755, 704 and 747 FANGVD29 in boreholes B115BD, B126BD, B137GP and B130GP, respectively. Three-arm caliper logs also indicate more than 1 in. of enlargement in borehole diameter between about 700 and 709 FANGVD29 in boreholes T1 (fig. A3, table 19) and T2. The caliper log from that part of borehole open to the Galena-Platteville deposits indicated areas of enlargement at about 502, 525, 582, and 664 FANGVD29 in borehole B305 and at about 458, 625 and 660 FANGVD29 in well BMW2 (fig. 35). Caliper logs from the remaining boreholes indicated little variation in borehole diameter.

Altitudes of increased borehole diameter identified with the caliper logs corresponded to the approximate location of possible fractures described by the lithologic logging in boreholes T1, T2, T6, and T8 (table 19). Altitudes of many intervals of increased borehole diameter identified with the caliper logs corresponded to the approximate location of possible fractures identified with camera logging in boreholes B128GP and well BMW2. Enlarged areas associated with the bottom of the casing in boreholes B115BD, B126BD, B130GP, and B137GP likely are artifacts of the drilling process on weathered rock rather than discrete secondary-permeability features.

Natural gamma

Natural-gamma logs run in boreholes B125BD, B115BD, B127GP, B128GP, and B127SP in the vicinity of the PCHSS were compared to the stratigraphic descriptions for these boreholes so the natural-gamma signal of the formations could be identified. Natural-gamma logs from these boreholes then were compared with natural-gamma logs from 22 other boreholes and wells located throughout the Belvidere area (figs. F1-F6, A3, 35, table 17) to provide additional understanding of the stratigraphy in the area and the lithology that may affect ground-water flow within the aquifer. However, as previously indicated, inconsistencies are associated with directly linking natural-gamma signatures with stratigraphic descriptions of the rock cores and the stratigraphic interpretations are subject to some degree of uncertainty. Compounding the designation difficulties are limitations in the resolution of depth measurements. Because the radius of investigation only is about 1 ft and signal sensitivity is affected by borehole diameter, errors in measurement of bedding depth and thickness may occur and the presence of thin beds, such as bentonite layers, may be obscured.

The logs provided a good indication of the relative increase in clay content from the Galena Group to the Platteville Group and readily distinguished the approximate positions of the argillaceous Glenwood Formation and non-argillaceous St. Peter Sandstone. Stratigraphy determined from the natural-gamma logs indicates that the Galena-Platteville deposits have a uniform thickness and are subhorizontal across the Belvidere area. Peaks in natural-gamma activity provided identification of at least two key marker beds at altitudes of about 525 and 660 FANGVD29. The marker bed at 660 FANGVD29 was identified to varying degrees in at least eight boreholes and wells distributed over the 1.5-mi^2 logging area and was present in all of the boreholes near the PCHSS. This marker bed appears to be either a potassium-bentonite deposit in the Wise Lake Formation or clay infilling of a prominent bedding-plane parting. The marker bed at 525 FANGVD29 also could be identified in boreholes distributed over the area, and appears to be the Stillman Member of the Grand Detour Formation. The altitude of the marker beds vary by as little as 5 ft indicating that the beds of the Galena and Platteville Groups essentially are flat-lying in this area. Anomalous features indicative of clay infilling of fractures were not observed.

Single-point resistance

SPR logging was done in eight boreholes and one well (table 17). SPR logs indicated an increase in signal response below the casing at about 742 FANGVD29 in borehole B115BD, indicated variable response in borehole B125BD, indicated essentially no change in borehole B126BD, and increased gradually between 704 and 744 FANGVD29 in borehole B127GP then remained essentially unchanged to the bottom of the borehole (fig. F3). The response of the SPR log for

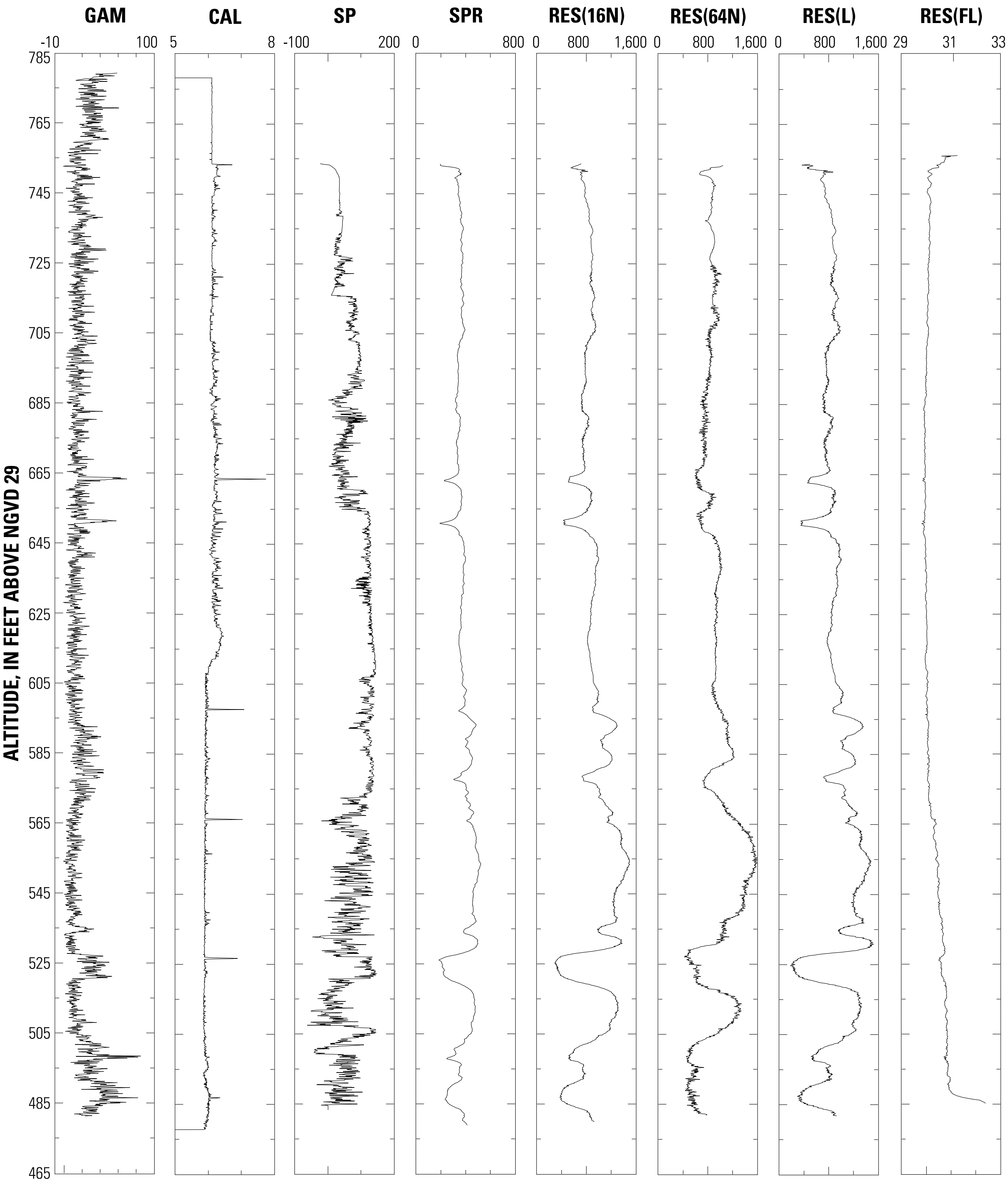
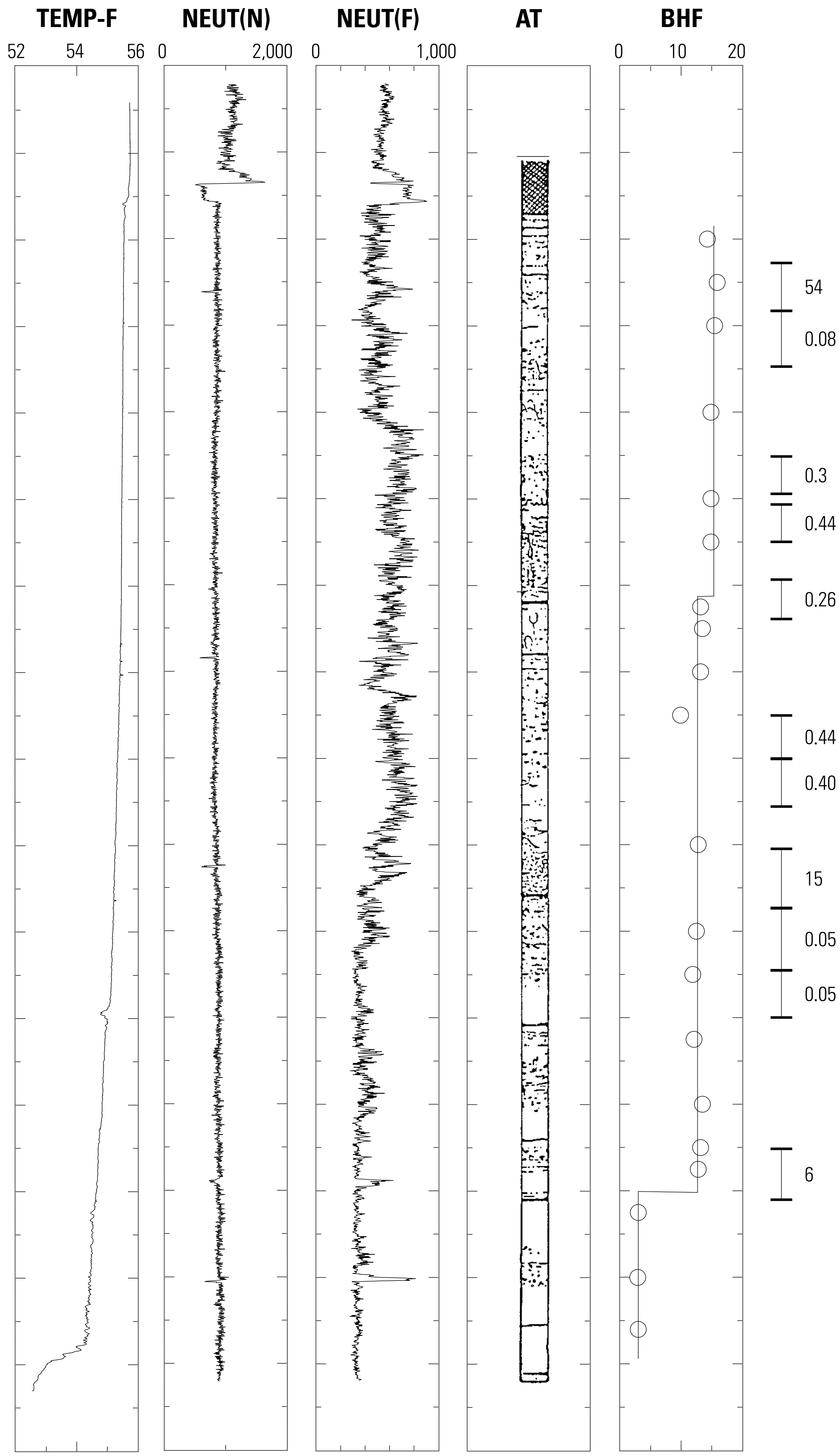


Figure F1. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G128GP in Belvidere, Ill.



EXPLANATION

GAM	NATURAL GAMMA, IN COUNTS PER SECOND
CAL	CALIPER, IN INCHES
SP	SPONTANEOUS POTENTIAL, IN OHMS
SPR	SINGLE-POINT RESISTANCE, IN OHM-METERS
RES(16N)	NORMAL RESISTIVITY-- 16 INCHES, IN OHM-METERS
RES(64N)	NORMAL RESISITVITY-- 64 INCHES, IN OHM-METERS
RES(L)	LATERAL RESISTIVITY, IN OHM-METERS
TEMP-F	TEMPERATURE, IN DEGREES FAHRENHEIT
NEUT(N)	NEUTRON--NEAR, IN COUNTS PER SECOND
NEUT(F)	NEUTRON--FAR, IN COUNTS PER SECOND
AT	ACOUSTIC TELEVIEWER
BHF	BOREHOLE FLOW, IN GALLONS PER MINUTE (GPM)
54	SLUG-TEST INTERVAL WITH HORIZONTAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY
○	DOWNFLOW, IN GALLONS PER MINUTE (GPM)

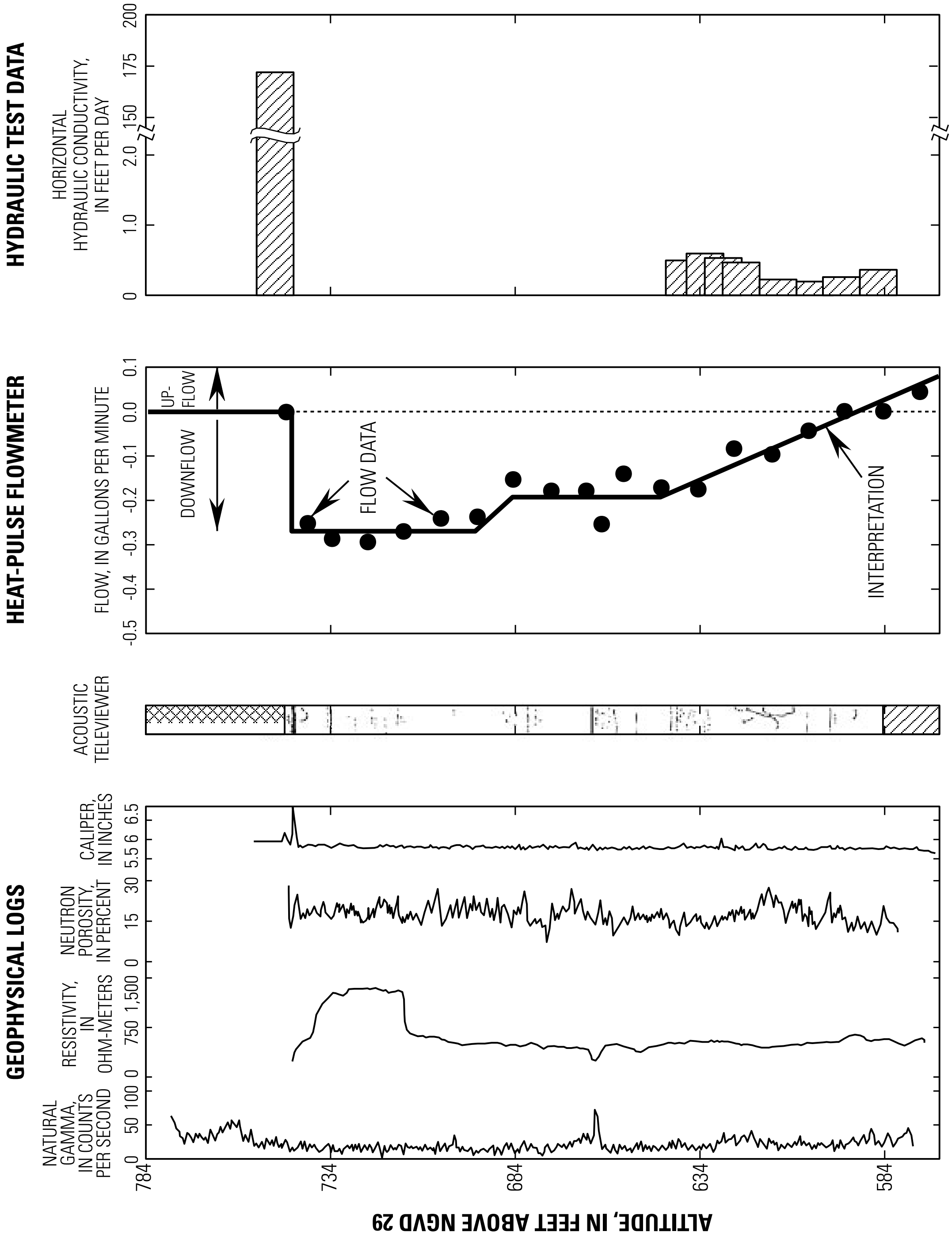


Figure F2. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole T6 in Belvidere, Ill.

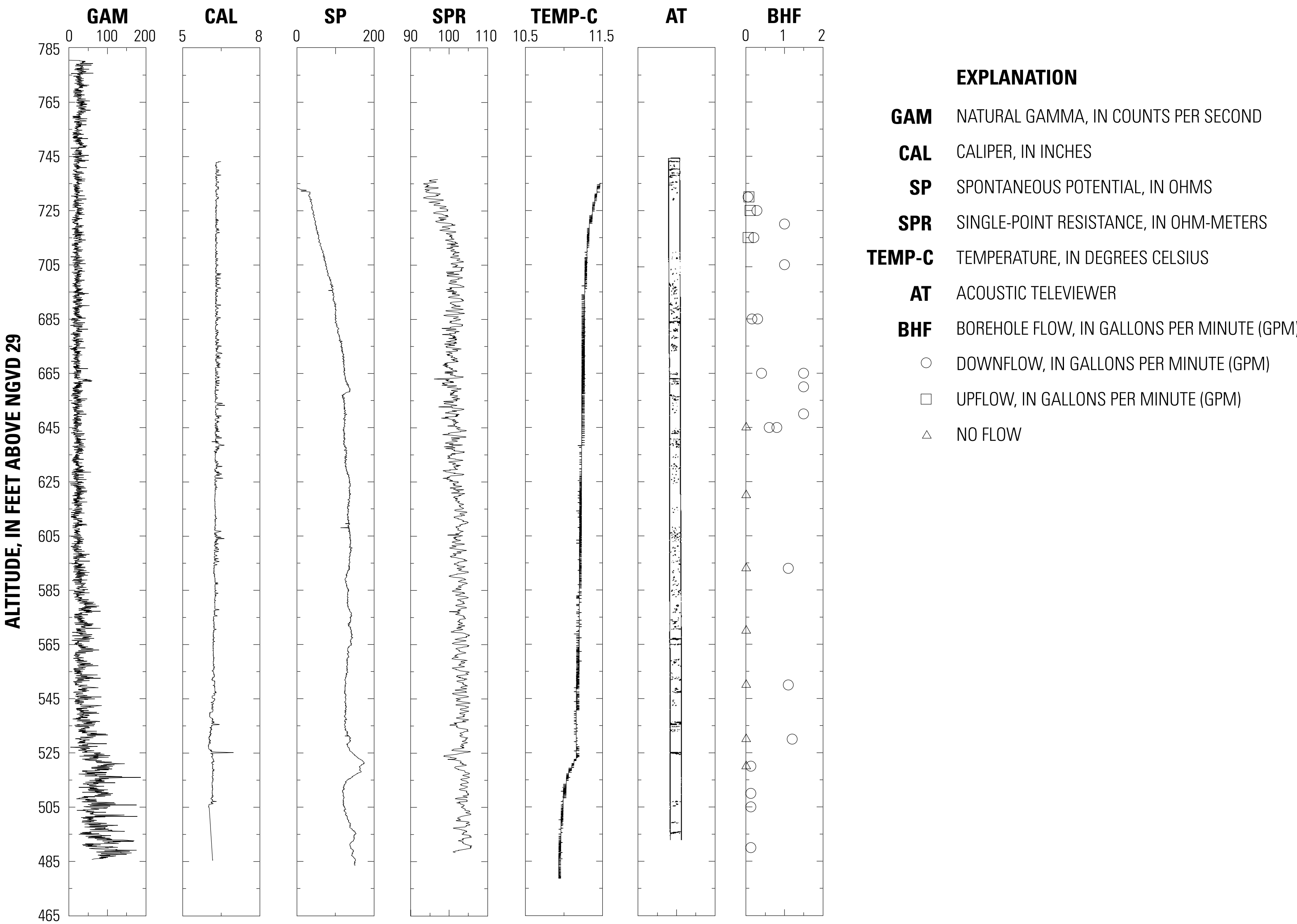


Figure F3. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G127GP in Belvidere, Ill.

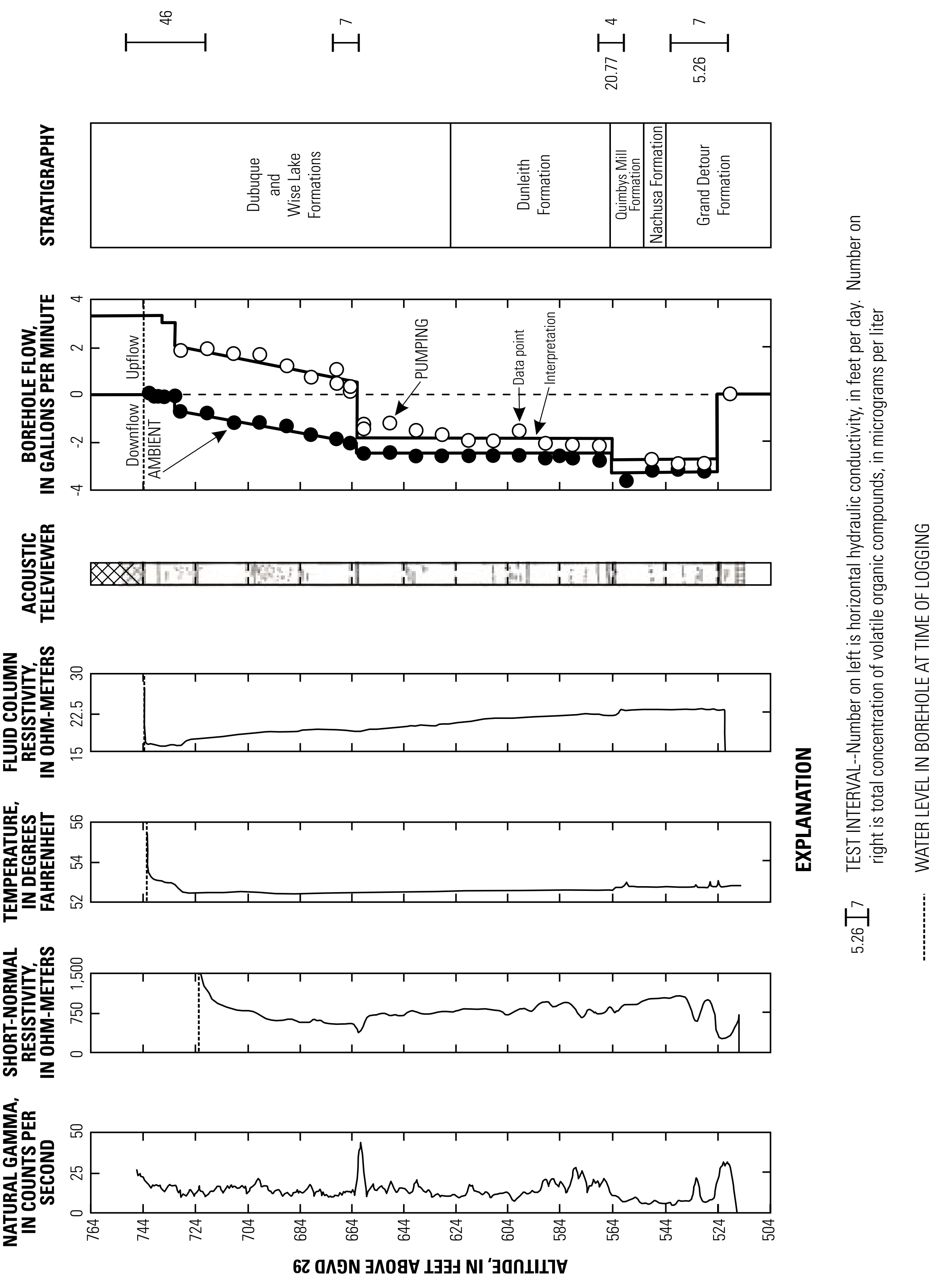


Figure F4. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G124GP in Belvidere, Ill.

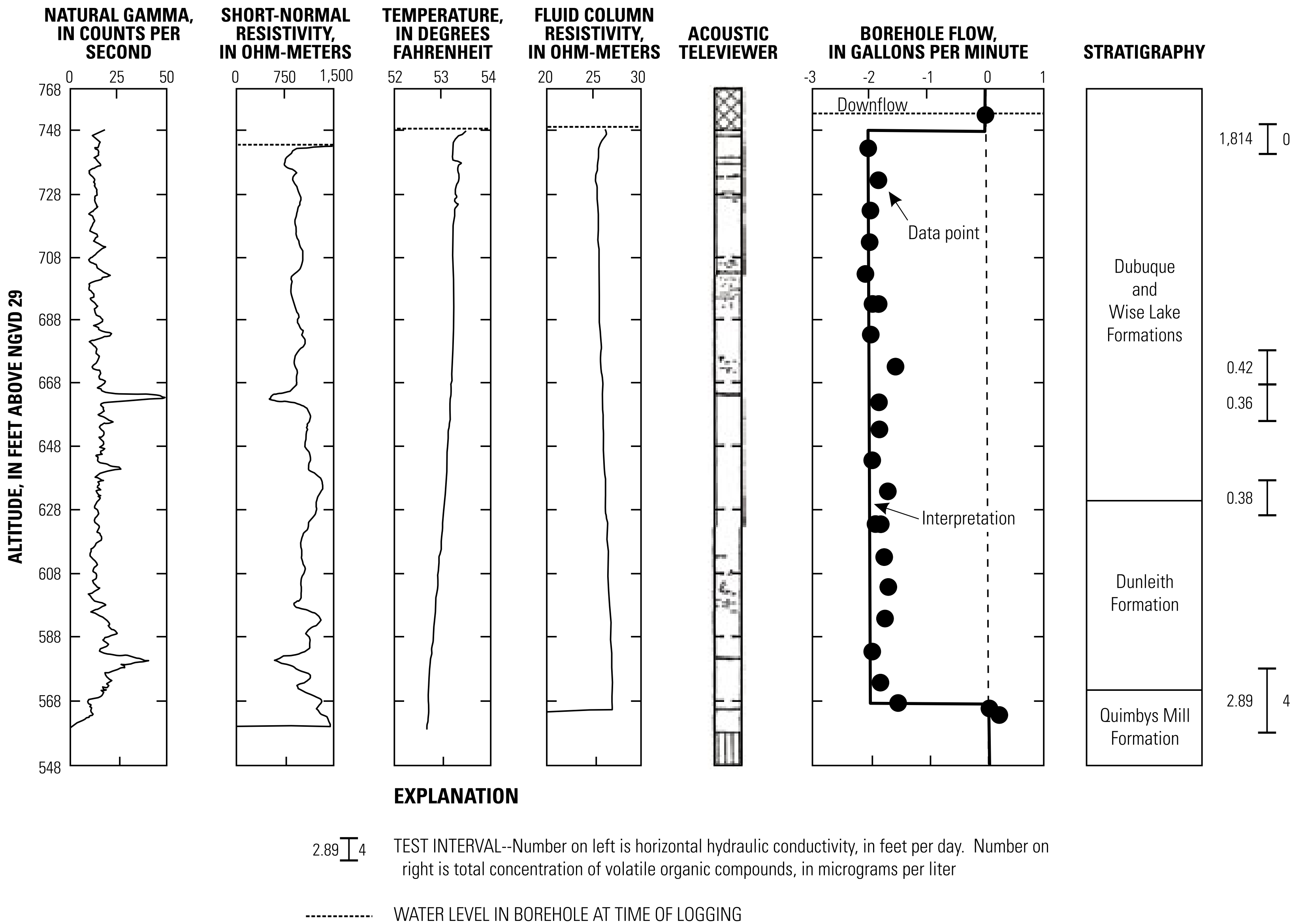


Figure F5. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G130GP in Belvidere, Ill.

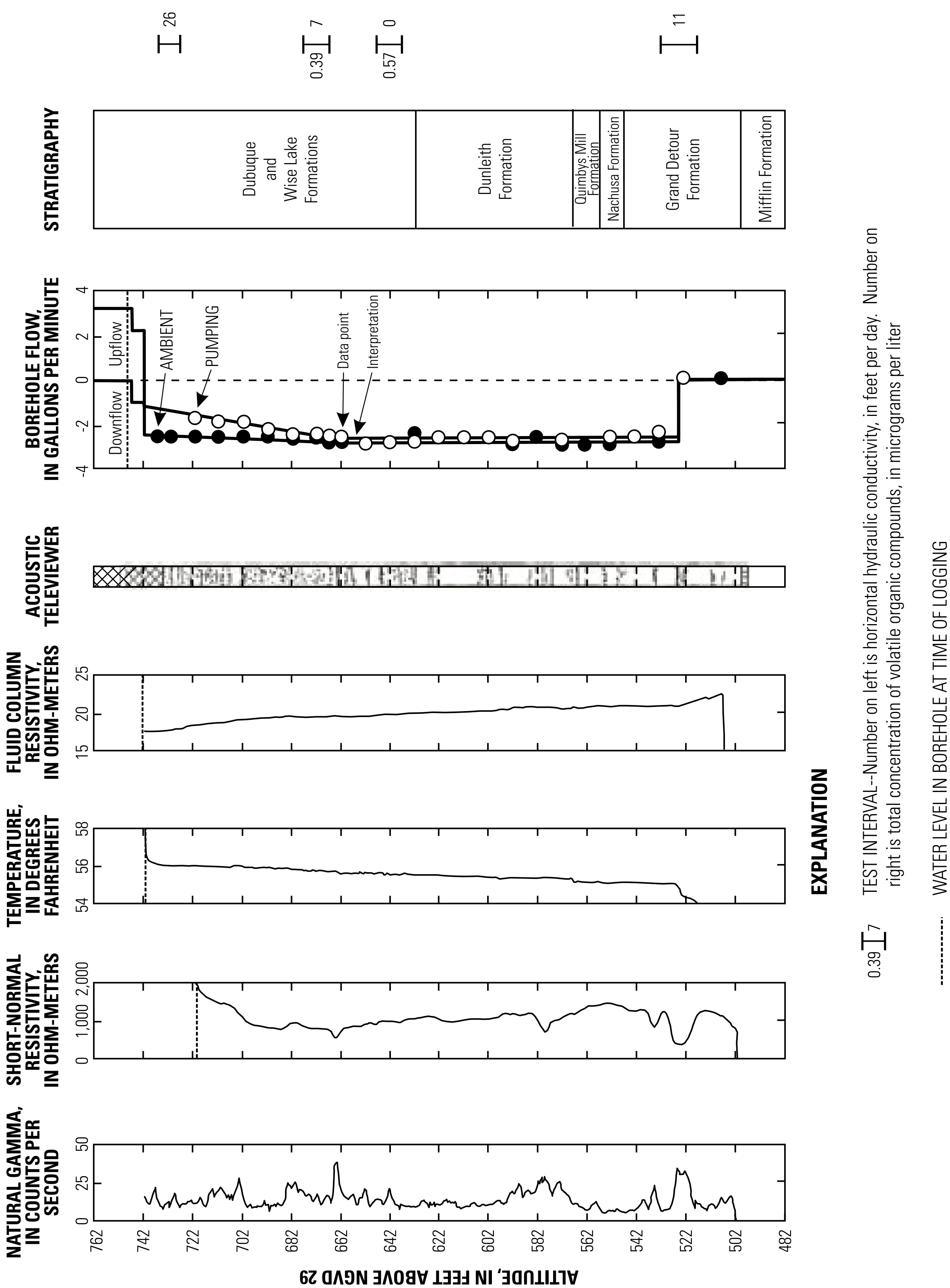


Figure F6. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G136GP in Belvidere, Ill.

that part of the borehole open to the Galena-Platteville deposits in borehole B127SP was consistent between about 494 and 747 FANGVD29, with the exception of sharp, isolated decreases in response at about 544, 554, and 683 FANGVD29. The response of the SPR log for borehole B128GPD indicated abrupt, isolated decreases in response at about 525, 575, 649, and 660 FANGVD29 (fig. F1, table 19). The response of the SPR log for borehole B436 generally was consistent throughout the borehole with the exception of a sharp decrease in response at about 660 FANGVD29. The SPR signal from that part of well BMW2 open to the Galena-Platteville dolomite indicates an abrupt decrease in signal response at about 485, 490, 525, and 660 FANGVD29. The SPR signal from the Galena-Platteville deposits at borehole B305 indicates abrupt decreases at about 490, 525, 582, and 664 FANGVD29.

SPR logs responded to some of the potential secondary-permeability features identified with other methods. Although never strong, the correlation was most consistent for the prominent 525-ft parting and less consistent for the 660-ft parting. In most cases, the SPR signal response was inversely correlated with natural-gamma activity or well diameter, as indicated by the three-arm caliper logs. As with SP logs, the resolution of the thickness and depth of a feature was less than that of caliper or natural-gamma logs.

Normal resistivity

Normal resistivity logging done in 14 boreholes and 1 well (figs. A3, F1, F2, F4, F5, F6; table 17) typically mirrored the signal responses of the SPR logs (fig. F1) and indicated an approximately inverse relation with natural-gamma response. High normal resistivity readings in the upper part of boreholes T6 and T1 were not detected during subsequent logging in these wells and these readings are assumed to be instrument error. Each of the logs typically responded in a similar manner, but signal responses usually were muted as the radius of investigation of the tool increased, 16-in. normal resistivity logs typically indicated substantially more detail than the 64-in. normal logs in boreholes G128GP, 00350, and B436, as well as well BMW2. SPR logs tended to indicate smaller changes in signal response than 16-in. normal resistivity logs, but more than 64-in. normal resistivity. This result indicates possible lithologic variations beyond the immediate vicinity of the boreholes.

Neutron

Near-well or far-well neutron logging was done at borehole B128GP (fig. F1) at the PCHSS. Near-well logging indicated a near-uniform count rate with small, distinct decreases in signal response at about 502, 525, 597, 646, and 732 FANGVD29 (table 19). Far-well logging, representing a larger radius of investigation than near-well logging, typically indicated about 400 cps from 484 to 580 FANGVD29 with small, distinct increases at about 502 and 525 FANGVD29. Higher count rates (and higher porosity) of about 600 cps were present from about 590 to 700 FANGVD29 with a small, distinct increase at about 597 FANGVD29. Count rates of about 500 cps were detected between about 702 FANGVD29 and the top of the Galena-Platteville dolomite at about 750 FANGVD29.

Neutron logs calibrated against porosity in boreholes T1 (fig. A3), T6 (fig. F2), and T8 at the PCHSS displayed variable response, but indicated lower porosity near the bottom of the boreholes at 569-594 FANGVD29 and near the top of the boreholes 709-760 FANGVD29 (table 19). Intervals of higher porosity were detected at 599-619, 664-674, and 684-709 FANGVD29. These patterns generally are consistent with those identified at borehole B128GP (table 19).

Although the absolute porosity values do not agree, variations in porosity identified from the neutron logs generally are consistent with the porosity variations identified from the analysis of the core samples. In particular, the elevated porosity in the 590-700 FANGVD29 interval at borehole B128GP and in parts of this interval at boreholes T1, T6, and T8 correlates well with the high porosity values (typically about 10-20 percent) determined from cores collected from the Galena Group (fig. 35). The lack of agreement between the two methods partly results because the neutron logs measure a larger volume of rock than the cores.

Neutron logs were more effective identifying variations in matrix porosity than in identifying potential fractures, presumably because the amount of water in the fractures is small in comparison to that in clay minerals and matrix porosity. Neutron logs (particularly the near-neutron logs) run in borehole B128GPD indicated some changes potentially associated with many of the potential secondary-permeability features identified with the caliper, SPR, or resistivity logs (fig. F1; table 19). However, these changes also correlate with areas of increased clay content identified with the natural-gamma logging, indicating the response may be caused more by water in the clays than by water in secondary-permeability features. Porosity values calculated from the neutron logs from borehole T6 indicated an increase associated with the potential secondary-permeability feature identified with the lithologic and caliper logging at 744 FANGVD29 (table 19), as well as at about 610-620 FANGVD29. However, these increases were not substantially different from nearby depths and the degree of response to the features is unclear. Porosity values obtained from the neutron log at borehole T1 did not indicate an increase associated with potential secondary-permeability features identified with lithologic and caliper logging.

Acoustic televiewer

Acoustic-televiewer logs indicate the presence of numerous bedding-plane partings through the entire thickness of all of the boreholes logged. Subhorizontal bedding-plane partings were identified at about 485, 494, 525, 564, and 660 FANGVD29 in every borehole open to those altitudes in the Belvidere area (figs. A3, F1-F6; tables 19, F1, F2) indicating that these are geographically widespread features. The 525-ft parting is associated with the top of the argillaceous part of the Grand Detour Formation and the 660-ft parting is associated with an argillaceous marker bed, indicating that lithologic characteristics (which may affect hydraulic characteristics) affect the location of these features. Numerous other prominent subhorizontal bedding-plane partings were identified within small parts of the Belvidere area, including one at about 744 FANGVD29 in boreholes T5-T8 at the PCHSS.

Acoustic-televiewer logs identified near-vertical fractures between about 699 and 709 FANGVD29 at boreholes T1 and T2 (same fracture) and between about 606 and 622 FANGVD29 in borehole T6 (figs. A3, F2). These fractures are subparallel with a strike of about N. 45^{o} E., which is consistent with the vertical fracture orientation identified with the SAR survey performed at the PCHSS. Near-vertical fractures were identified in borehole B134GP at about 550 and 715 FANGVD29. The fracture at 715 FANGVD29 has a strike of about N. 19^{o} W., whereas the fracture at about 550 FANGVD29 has a strike of about N. 79^{o} W. A near-vertical fracture identified at about 630 FANGVD29 in well BMW2 has a strike of about N. 45^{o} W. These measurements approximate the predominant orientation (about N. 60^{o} W.) of other inclined fractures in the area, as determined at local quarries (Foote, 1982; Mills and others, 2002a), and are consistent with the vertical-fracture orientations identified with the SAR surveys at the Irene (N. 30^{o} W.) and Stone Quarry Road sites (N. 60^{o} E. and N. 45^{o} W.).

Acoustic-televiewer logs also indicate the presence of vuggy intervals throughout the dolomite, with the formations composing the Galena Group being vuggier than most of the formations (except possibly the Nachusa Formation) that compose the Platteville Group (figs. A3, F1-F6). Vugs generally are most evident in the altitude interval at about 550-660 FANGVD29. Vuggy intervals were detected at about 684-704 and 724-734 FANGVD29 in borehole B124GP (fig. F4), at 693-708 FANGVD29 in borehole B130GP (fig. F5), 673-698 FANGVD29 in borehole B133GP, above 662 FANGVD29 in borehole B136GP (fig. F6), above about 574 FANGVD29 in borehole B137GP, at about 600-640 and 682-702 FANGVD29 in boreholes T1-T8 (figs. A3, F2), at about 570-604, 624-654, 672-706 FANGVD29 in borehole B127GP (fig. F3), and at about 500-510, 540-560, 570-600, and 660-720 FANGVD29 in borehole B128GP (fig. F1). Vuggy intervals identified with the televiewer logs generally indicated moderate agreement with intervals of increased porosity identified with the neutron logs in boreholes T1, T6, T8, and B128GPD (table 19). Vuggy intervals identified with the televiewer logs typically are similar to those identified with borehole-camera logging, and visual inspection and porosity measurement of cores. Although vugs were recorded in other intervals, comparison with rock cores indicated that, in some cases, the apparent vugs may be small cavities that are well-drilling artifacts.

Acoustic-televiewer logs confirmed the presence of numerous vugs and bedding-plane partings that were identified with other methods (table 19). For example, in each borehole where a parting was identified in the lithologic and caliper logs, the parting also was identified in the acoustic-televiewer log. This relation particularly is true for the 660- and 525-ft partings. Acoustic-televiewer logs also identified partings that were not apparent based on other methods. For example, a parting at an altitude of about 485 FANGVD29 in borehole B128GP (referred to in previous reports as the 300-ft parting based on depth at the PCHSS and referred to as the 485-ft parting in this report) was identified with the televiewer logs, but was not apparent in the camera log, rock core, or other geophysical logs. Additionally, televiewer logs enabled identification of the type and orientation of secondary-permeability features that could not be identified with other methods except camera logging. However, bedding-plane partings identified in the acoustic-televiewer logs should be verified with caliper and natural-gamma logs, as well as other data, because signal responses on acoustic-televiewer logs can be similar for wash outs of argillaceous material (including shale partings and bentonite beds) and fractures.

Borehole ground-penetrating radar—single hole

A single-hole directional GPR reflection survey done in borehole B127GP at the PCHSS in 1991 (Niva, 1991; J.W. Lane, Jr., U.S. Geological Survey, written commun., 1993; Mills and others, 1998) was capable of signal penetration about 50 ft into the dolomite. Interpretation of the radar data from this survey indicated the presence of 35 reflectors in the vicinity of the borehole (Mills and others, 1998)(table F2). Most of the reflectors are considered to represent bedding-plane partings (including the 525- and 660-ft partings) and isolated cavities. The cavities, if present, are assumed to be small; large cavities (greater than about 1 in^3) have not been detected with other methods.

Dips of the GPR reflectors interpreted as fractures (excluding the bedding-plane fracture assumed to represent the 525-ft parting) range from about 33^{o} to 86^{o}. The

Table F2. Summary of orientation of fractures and reflectors in select boreholes by method of detection, Belvidere III.

[Bold denotes reflectors calculated to intercept the borehole above or below the open interval of the borehole. NI, not identified; ND, no data; F, fracture; BPP, bedding-plane parting; P, point feature; NA, not applicable; NC, could not be calculated]

Borehole name	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Acoustic Televiewer			Single-hole ground-penetrating radar reflectors		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of feature	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of reflector
T1	**813.5**	NI	NI	NI	N 50° E	82.0	F
	753.1	NI	NI	NI	S 70° W	43.4	F
	729.5	NI	NI	NI	NC	52.5	F
	700-709	N 43° E	88	F	NI	NI	NI
	664.2	NA	0	BPP	N 50° E	49.9	F
	658.3	NI	NI	NI	N 30° E	.0	BPP
	657.7	NI	NI	NI	NC	16.6	F
	651.0	NA	0	BPP	NI	NI	NI
	640.2	NI	NI	NI	NC	38.9	F
	632.1	NI	NI	NI	NC	52.5	F
	631.1	NA	0	BPP	NC	36.4	F
	601.0	NA	0	BPP	NI	NI	NI
	577.0	NI	NI	NI	NC	57.9	F
	574.0	NI	NI	NI	N 90° E	51.6	F
	515.3	NI	NI	NI	S 60° E	65.4	F
	503.1	NI	NI	NI	S 50° E	72.4	F
T6	**2922.0**	NI	NI	NI	NC	89.1	F
	812.5	NI	NI	NI	NC	74.3	F
	769.2	NI	NI	NI	S 70° W	55.3	F
	745.0	NA	0	F	NI	NI	NI
	734.0	NA	0	F	NI	NI	NI
	689.8	NI	NI	NI	N 40° E	40.1	F
	678.7	NI	NI	NI	S 40° W	41.3	F
	662.0	NA	0	F	NI	NI	NI
	659.0	NI	NI	NI	N 40° E	.0	BPP
	652.1	NI	NI	NI	NC	56.7	F
	629.8	NI	NI	NI	NC	ND	F
	628.2	NI	NI	NI	NC	40.9	F
	604-620	N 50° E	88	F	NI	NI	NI
	568.1	NI	NI	NI	S 10° W	64.6	F
	513.7	NI	NI	NI	S 70° W	74.9	F
T8	744.9	NA	0	F	N 30° E	38.3	F
	732.0	NA	0	BPP	NI	NI	NI
	700.0	NA	0	BPP	NI	NI	NI
	688.2	NI	NI	NI	N 60° E	34.5	F
	675.0	NI	NI	NI	NC	27.8	F
	660.0	NA	0	BPP	NI	NI	NI
	656.3	NI	NI	NI	N 50° E	.0	F
	649.0	NA	0	BPP	NI	NI	NI
	612.7	NI	NI	NI	S 10° W	50.0	F

Table F2. Summary of orientation of fractures and reflectors in select boreholes by method of detection, Belvidere Ill. --Continued.

Borehole name	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Acoustic Televiewer			Single-hole ground-penetrating radar reflectors		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of feature	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of reflector
T8 (cont.)	**551.4**	NI	NI	NI	N 40° E	52.6	F
	526.7	NI	NI	NI	N 10° E	70.3	F
B127GP	**1380.0**	NI	NI	NI	NA	85.6	F
	1027.0	NI	NI	NI	S 40° W	83.7	F
	933.0	NI	NI	NI	N 70° W	78.4	F
	909.0	NI	NI	NI	NC	76.0	F
	834.0	NI	NI	NI	N 90° W	66.5	F
	770.8	NI	NI	NI	NC	51.3	F
	745.0	NA	0	F	NI	NI	NI
	740.0	NA	0	BPP	NI	NI	NI
	738.0	NA	0	BPP	NI	NI	NI
	732.1	NA	0	BPP	NC	52.8	F
	731.8	NA	0	BPP	NA	.0	BPP
	704.6	NI	NI	NI	NA	.0	BPP
	685.6	NA	0	BPP	NA	.0	BPP
	680.3	NA	0	BPP	NA	.0	BPP
	673.8	NI	NI	Vugs?	NA	.0	BPP
	662.0	NA	0	F	NI	NI	NI
	658.3	NI	NI	Vugs?	NA	NA	P
	657.4	NA	0	BPP	NA	.0	BPP
	640.3	NA	0	BPP	NA	NA	P
	639.0	NA	0	BPP	NC	48.9	F
	637.4	NI	NI	NI	NA	.0	BPP
	637.0	NI	NI	NI	NA	NA	P
B127GP	622.3	NI	NI	Vugs?	NA	NA	P
	606.2	NI	NI	Vugs?	N 0° E	69.8	F
	595.0	NI	NI	NI	NA	.0	BPP
	588.8	NI	NI	NI	NA	NA	P
	572.4	NA	0	BPP	NA	.0	BPP
	566.0	NA	0	BPP	NI	NI	NI
	564.0	NA	0	BPP	NI	NI	NI
	538.0	NI	NI	NI	NA	NA	P
	535.0	NA	0	BPP	NI	NI	NI
	525.0	NA	0	BPP	NC	10.2	F
	507.8	NI	NI	NI	NA	.0	BPP
	502.5	NI	NI	NI	NA	NA	P
	499.6	NI	NI	NI	NA	46.3	F
	498.6	NI	NI	NI	ND	NA	P
	497.6	NI	NI	NI	NA	NA	P
	495.7	NA	0	BPP	NC	63.2	F
	479.9	NI	NI	NI	N 50° W	71.0	F
	475.0	NI	NI	NI	N 70° W	32.8	F
	469.1	NI	NI	NI	N 90° W	61.7	F
	111.9	NI	NI	NI	N 80° W	84.2	F

strike of the reflectors tends to be randomly oriented, ranging from N. 0° W. to N. 140° W.; however, orientations at six of the eight fractures with measured strikes range from N. 50° W. to N. 90° W. These orientations are consistent with measurements at quarries and outcrops in the Belvidere area (primary orientation of about N. 60° W.) (Foote, 1982), but indicate poor agreement with the results of the SAR survey performed within 20 ft of this borehole.

Only six of the GPR reflectors interpreted as inclined fractures are calculated to intersect the open interval of the borehole (table F2). However, fractures were not identified with televiewer or other methods at any of these depths (table F2). Four of the possible fractures identified in GPR logging of B127GP have been interpreted as intercepting the borehole trace about 30 ft above or 300 ft below the Glenwood Formation. Such fractures, if extending to these depths, would penetrate the lower part of the Galena-Platteville dolomite to a depth greater than that typically indicated in other carbonate units in northern Illinois (Csallany and Walton, 1963).

Single-hole directional GPR-reflection surveys done in boreholes T1, T3, T6, and T8 at the PCHSS in 1996 were capable of signal penetration about 15-30 ft into the dolomite (Lane and others, 1994). Between 8 and 13 reflectors were identified in the vicinity of these boreholes (table F2). Aside from a horizontal reflector associated with the 660-ft parting, all of the reflectors were interpreted as inclined fractures, with two distinct orientations. The most frequently interpreted direction of reflector strike near boreholes T1, T3, T6, and T8 is N. 30° E. to N. 50° E. and its counterpart from S. 30° W. to S. 50° W. This orientation is consistent with the inclined fracture orientations identified with the acoustic-televiewer logs boreholes T1, T2, and T6 and the SAR survey done near borehole B127GP. The less frequently interpreted direction of reflector strike is roughly north-south from N. 30° E. to N. 10° W. and its counterpart from S. 30° W. to S. 10° E. Most of the reflectors dip between 40 and 60 degrees from horizontal. Dip values determined from the reflection surveys tend to be substantially less than the values determined from televiewer logging.

A reflector that appears to be the near-vertical fracture identified with the televiewer logging in boreholes T1 and T2 was identified with the GPR reflection survey in borehole T3. This fracture was not identified during the reflection survey done in borehole T1. The reflector terminates below about 610 FANGVD29. The fracture probably extends some distance below this altitude, but it is likely that the size of the fracture decreases with depth and does not produce a strong enough response for the reflector to be identified. The inclined fracture identified at 608-622 FANGVD29 with the televiewer log in borehole T6 was not identified with the single-hole GRP survey.

The type, location, and orientation of secondary-permeability features identified with the single-hole direction GPR surveys indicated moderate agreement with those identified using the other methods (tables F2, 19). The 525-ft and 660-ft partings were identified with the GPR surveys and other reflectors interpreted as bedding-plane partings may represent some of the small partings or vuggy intervals indicated with other logs. However, the altitude of the other bedding-plane partings identified with the GPR logs typically vary by 5 ft or more from those identified with other methods. The offsets in depth do not seem consistent, thus, depth differences do not seem accounted for by a difference in reference datums for measurements. Orientations of inclined fractures determined from the GPR logging in the T series of boreholes were consistent with those identified with the televiewer logs and with the SAR survey done within 20 ft of borehole B127GP. However, these orientations varied considerably between boreholes T1, T3, T6, and T8 and borehole B127GP, a distance of less than 150 ft. Fracture orientations determined at borehole B127GP could represent the orthogonal counterpart of the fracture sets in the nearby boreholes. Additionally, many of the inclined fractures identified with the GPR logging were not identified with other logs at the altitude the fracture was calculated to intersect the borehole. The number of inclined fractures identified with televiewer logs intersecting a given borehole also was substantially lower than indicated with the GPR surveys. This discrepancy may result because of termination of the fracture before it intercepts the borehole, which may indicate decreasing fracture size and density with depth in the Galena-Platteville dolomite.

Borehole ground-penetrating radar—cross-hole

Cross-hole GPR surveys done at the PCHSS between the T2-T7, T2-T8, T2-T3, T3-T8, T3-T7, and T7-T8 borehole pairs differentiate the Galena-Platteville dolomite into three units (Lane and others, 1994). The lower unit is present between about 567 (the bottom of these boreholes) and about 602 FANGVD29 and is characterized by low signal attenuation and high velocity consistent with competent dolomite (table F3). The porosity for this unit, based on the calibrated GPR signal, was from 12 to 13 percent. The middle unit is present at 602-700 FANGVD29 and is characterized by low velocity with interspersed beds of high and low attenuation, which is indicative of competent dolomite with intervals of variable porosity. The porosity of most of the middle unit was calculated to be about 13 percent, with porosity of about 13.5-14 percent at about 667 FANGVD29 and between 681 and 693 FANGVD29, porosity of about 13.5-15 percent at about 605-615 FANGVD29, and porosity of about 12-13 percent at about 676 FANGVD29. The upper unit extends from about 700 FANGVD29 to about 5 ft below the bottom of the casings (about 744 FANGVD29), where the signal was lost. The upper unit is characterized by low signal attenuation and high velocity consistent with competent dolomite. The porosity of the upper unit was estimated to be about 11-12.5 percent from the GPR signal. Although the absolute values for porosity from the GPR logs was lower than for the neutron logs from boreholes T1 and T6, the trends in porosity were similar for both logs (table 19). Porosity values measured in the core samples were consistent with the values obtained from the GPR survey.

Water-level measurements

A synoptic measurement of water levels from wells distributed throughout the Belvidere area was done to evaluate horizontal flow directions. Water levels also were measured in selected monitoring and water-supply wells in the Belvidere area for evaluation of (1) vertical flow directions, (2) hydraulic connection within and between aquifers, (3) the location of permeable features, and (4) response to climatological events and withdrawals from water-supply wells.

Synoptic measurements

During July 1993, water levels were measured in about 150 wells in the Belvidere area; about 50 of which were open to the Galena-Platteville aquifer (Mills and others, 1999a, b)(table 17). Water levels were measured in monitoring wells at the PCHSS and the rest of the Belvidere area, but most of the water levels were measured in residential-supply wells. More than half of these wells were located in subdivisions and some water levels likely were affected by nearby withdrawals. About 80 percent of the wells open to the Galena-Platteville aquifer were open only to the upper half of the aquifer and conclusions regarding water-level trends and flow directions may not be representative of the deeper parts of the aquifer. Surface-water levels were measured at the Kishwaukee River to supplement ground-water levels in the glacial drift aquifer above the Galena-Platteville aquifer.

Water levels in the Galena-Platteville aquifer ranged from about 740 to 900 FANGVD29 and were similar to those within the overlying glacial drift aquifer (figs. 34a, 34b). Data from well clusters open to both the glacial drift and Galena-Platteville aquifers indicated that the potentiometric surface of the glacial drift aquifer generally is less than 1 ft higher than that of the upper part of the Galena-Platteville aquifer and about 5-10 ft higher than that of the middle part of the Galena-Platteville aquifer. The potentiometric surface of both aquifers mimics the configuration of land-surface topography, indicating that the aquifers are unconfined. Horizontal flow generally is toward the Kishwaukee River and its principal tributaries. Vertical flow generally seems to be downward. The availability of wells, particularly in and near Belvidere, was insufficient to map possible flow toward the Troy Bedrock Valley, drawdown associated with municipal-well withdrawals, or areas of upward flow associated with discharge. However, there are a number of areas within the Belvidere area, particularly in the city of Belvidere, where the water level in the Galena-Platteville aquifer is substantially lower than in surrounding areas (fig. 34b). These areas of lower water

Table F3. Summary of ground-penetrating radar tomographic anomalies, Belvidere, Ill.

[<, less than altitude of bottom of borehole; 737*, top of signal reading; d, discontinuous feature]

Borehole pair	Altitude of low-velocity intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of high-velocity intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of low-attenuation intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of high-attenuation intervals (feet above National Geodetic Vertical Datum of 1929)
T2-T7	611.5, 648d, 664, 674.5, 690	<567-602, 677, 700-737*	<567-602, 611.5, 700-737*	641, 661, 677-700 by well T2
T2-T8	611.5, 648d, 664, 674.5, 691	<567-602, 701-737*	<567-618, 618-737*	644, 661, 677
T3-T2	611.5, 651-684	<567-602, 701-737*	703-737*	651-667
T3-T8	615, 648d, 667, 690	<567-592, 710-737*	<567-608, 611.5, 700-737*	638, 657.3
T7-T3	611.5, 644d, 667, 690	<567-602, 704-737*	<567-618, 704-737*	Alternating high and low; 628-664
T7-T8	615, 648d, 667, 690	<567-600, 704-737*	<567-615, 700-737*	657.3-661

levels appear to be associated with pumping from quarries, and municipal- and industrial-supply wells.

Continuous measurements

Continuous measurements of water levels were made in boreholes and wells at different times (table 17). Continuous measurements were important for identifying the climatic and anthropogenic factors affecting water levels and the variability of flow direction as well as the locations of permeable features within the Galena-Platteville aquifer underlying the Belvidere area.

Water levels were measured on a 15-minute sampling frequency in wells G115D, G115B, G126BGP, and G127SP at the PCHSS during November and December 1992. Continuous measurements did not indicate a rapid response to precipitation events in the Galena-Platteville aquifer (fig. F7a), but did indicate pronounced short-term (seconds to hours) hydraulic responses to pumping and the termination of pumping in nearby municipal-supply wells (fig. F7c). Water levels in well G127GP, open to the deep part of the Galena-Platteville aquifer at about 490 FANGVD29 (depth of about 295 ft), changed by about 25 ft in almost instantaneous response to initiation or cessation of withdrawals at municipal well BMW6. Well BMW6 is located within 100 ft of well G128GP (fig. 31) and is open, in part, to the Galena-Platteville aquifer, although most of the water is taken from the St. Peter Sandstone and other underlying aquifers. Similar, but more subdued responses to withdrawals are indicated in wells open to shallower parts of the aquifer (fig. F7a). For example, water levels in well G115BD, open at about 630 FANGVD29 (depth about 150 ft), frequently changed by about 3 ft in the span of less than 1 day. Water levels in well G115B, open at about 730 FANGVD29 (depth of about 50 ft), typically changed by less than 0.1 ft during the same period. Water levels in these wells also responded to pumping in well BMW4, although to a lesser degree than to pumping in well BMW6.

Water-level responses similar to those described above also were recorded at well G305GPC in the central part of Belvidere in November and December 1992. Water levels in well G305GPD, open to the 525-ft parting, dropped as much as 7 ft in apparent response to withdrawals at well BMW5 located more than 0.5 mi away. Water-level response in well G305GPS, open to the 660-ft parting, was negligible.

The water-level responses described above are consistent with those observed during subsequent continuous monitoring events done in a variety of monitoring wells and in borehole test intervals isolated with a packer assembly. Water levels in monitoring wells or test intervals open to the 525-ft parting typically fluctuated by 5-30 ft in almost instantaneous response to pumping in the municipal-supply wells. Water levels in wells or test intervals open to progressively shallower parts of the Galena-Platteville aquifer also had almost instantaneous response to pumping but with progressively smaller fluctuations. Subsequent monitoring indicates that pumping stresses from the municipal-supply wells were not transmitted to the upper part of the Galena-Platteville aquifer or the glacial drift aquifer, at least in the vicinity of the PCHSS.

Water levels also were collected at a 15-minute frequency in monitoring wells G124GP, G133GP, G134GP, and G136GP during February 2000 (fig. F8). All of these wells were open to the 525-ft parting, and all responded to pumping in wells BMW4, BMW6, and perhaps nearby industrial-supply wells (fig. 30). Water-level fluctuations in well G124GP, located nearest BMW6, tended to be largest and usually were in excess of about 6 ft daily. Water-level fluctuations in well G136GP tended to be intermediate, and fluctuations in wells G133GP and G134GP tended to be lowest, usually about 4 ft during a day. Changes in water level during pumping usually were substantial enough to alter flow directions in the 525-ft parting from its typical direction south toward the Kishwaukee River to north toward well BMW6. Water levels in wells G124GPS, G134GPS, and G136GPS, open to the upper 15 ft of the Galena-Platteville aquifer, did not respond to pumping.

Analysis of the continuous water-level data indicate that the 525-ft parting located throughout at least the center part of the Belvidere area is permeable, and is connected to the open intervals in BMW4, BMW5, and BMW6, and perhaps other domestic, industrial- and municipal-water-supply wells in Belvidere. Deep, widespread, permeable bedding-plane partings (such as the 485-ft parting) also may be present, but the relative unavailability of monitoring points open to the aquifer below 525 FANGVD29 precluded verification of the presence of such features. Pumping and the termination of pumping in the municipal-supply wells induces large, instantaneous water-level changes in the 525-ft parting, which are transmitted vertically within the aquifer through a hydraulically interconnected network of vugs and inclined fractures. These water-level changes are sufficient to alter flow directions within the deeper part of the aquifer, but are attenuated in the upper part of the aquifer. The dampening of the water-level change with increasing vertical distance above the 525-ft parting indicates an increase in the capacity of the aquifer to respond to the hydraulic stress induced by drawdown in the 525-ft parting by flow from storage and permeable features. This response is consistent with an increasing well developed network of secondary-permeability features with decreasing depth in the Galena-Platteville aquifer.

The effect of nearby ground-water withdrawals on the approach taken for water-level measurement in this

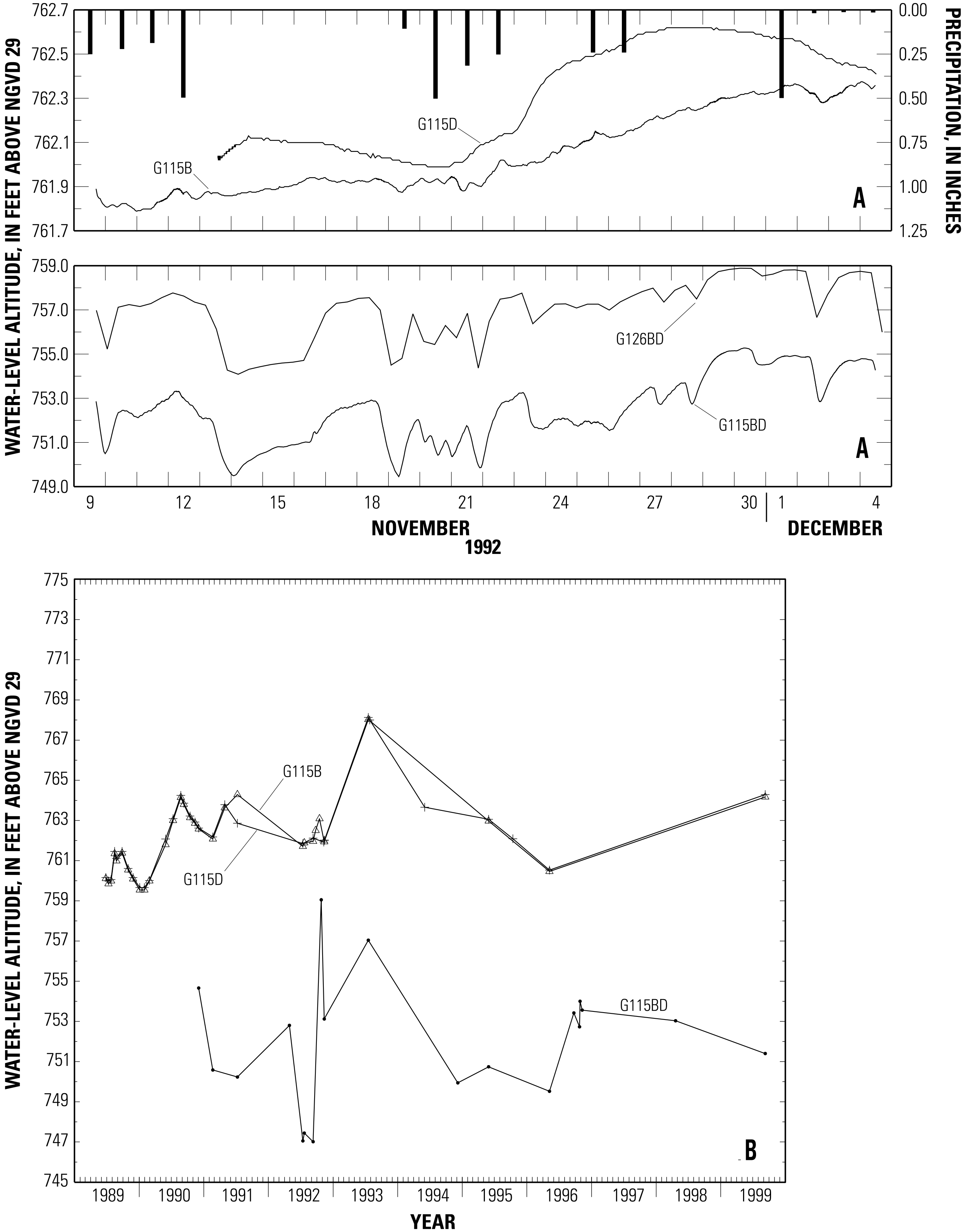


Figure F7. Hydrographs for select wells open to the Galena-Platteville and adjacent aquifers underlying Belvidere, Ill., showing response to (A) precipitation, (B) climatological trends, and (C) withdrawals from high-capacity supply wells.

urban setting should be considered. In some wells, water levels usually changed so rapidly and to such an extent that accurate measurement with a steel tape and chalk was impractical to impossible; use of an electric-sensor tape generally was necessary for water-level measurements. Also, when storing a reference water level in an automatic data logger, setting the reference level immediately following manual measurement was necessary to avoid error in the reference level for subsequent automatic measurements.

Periodic measurements

Water levels were measured periodically in 11 wells located in the city of Belvidere (table 17). Measurements were made during field trips at time intervals that typically ranged from less-than hourly to annually. These data provided information on longer-term water-level trends (up to 12 years) in response to climatalogical trends and (or) ground-water use (fig. F7b). Over the period of measurement, water levels at all depths of the Galena-Platteville aquifer varied by about 5-10 ft, typically in response to long-term variations in recharge. The greatest increase in water levels was in 1993, in response to an unusually large amount of precipitation that year (greater than 150 percent of annual average). During other periods, water levels typically varied by about 5 ft or less. Water levels measured in the deeper parts of the aquifer, such as well G115BD, were affected by ground-water withdrawals as well as long-term trends

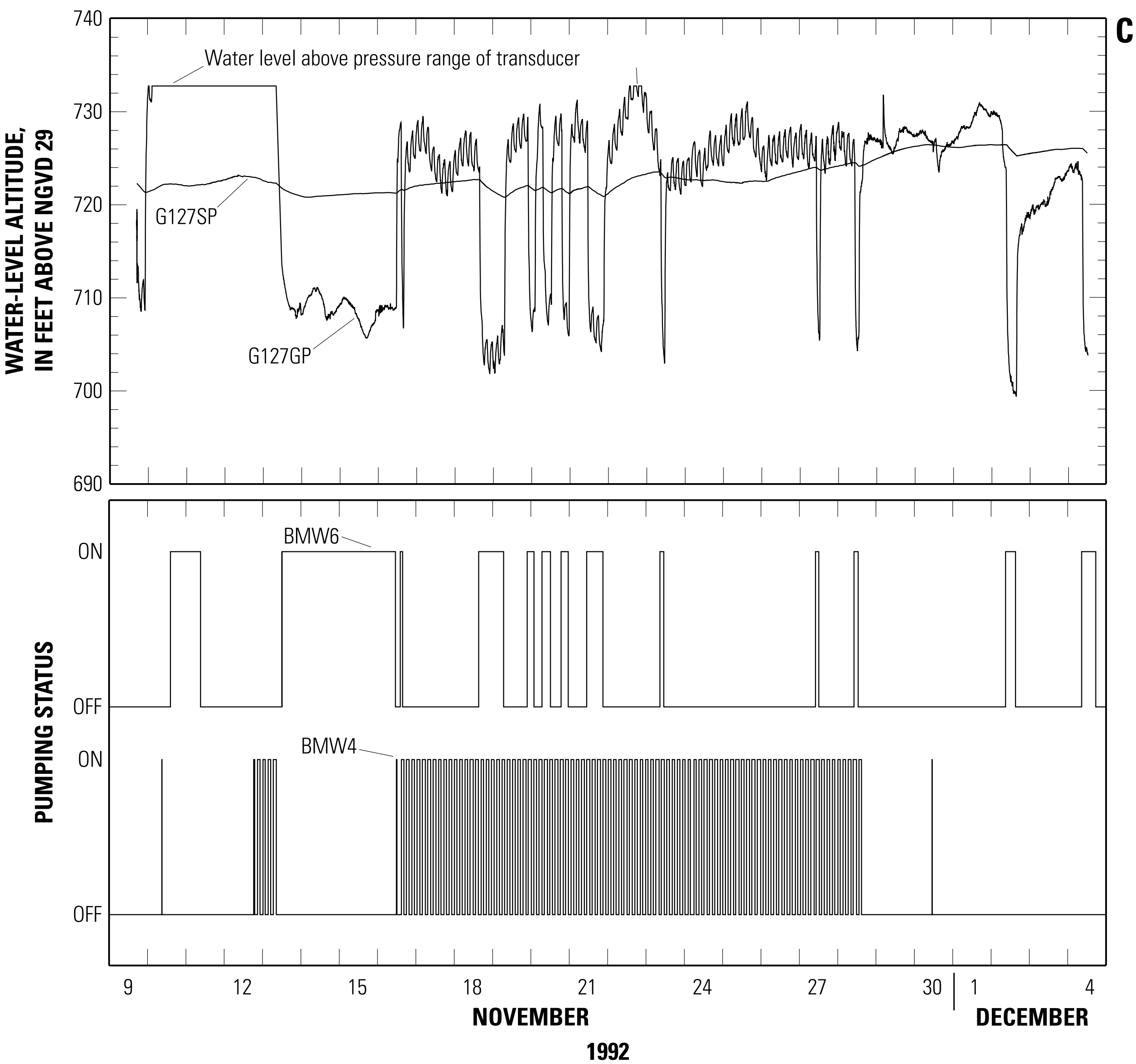


Figure F7. Continued.

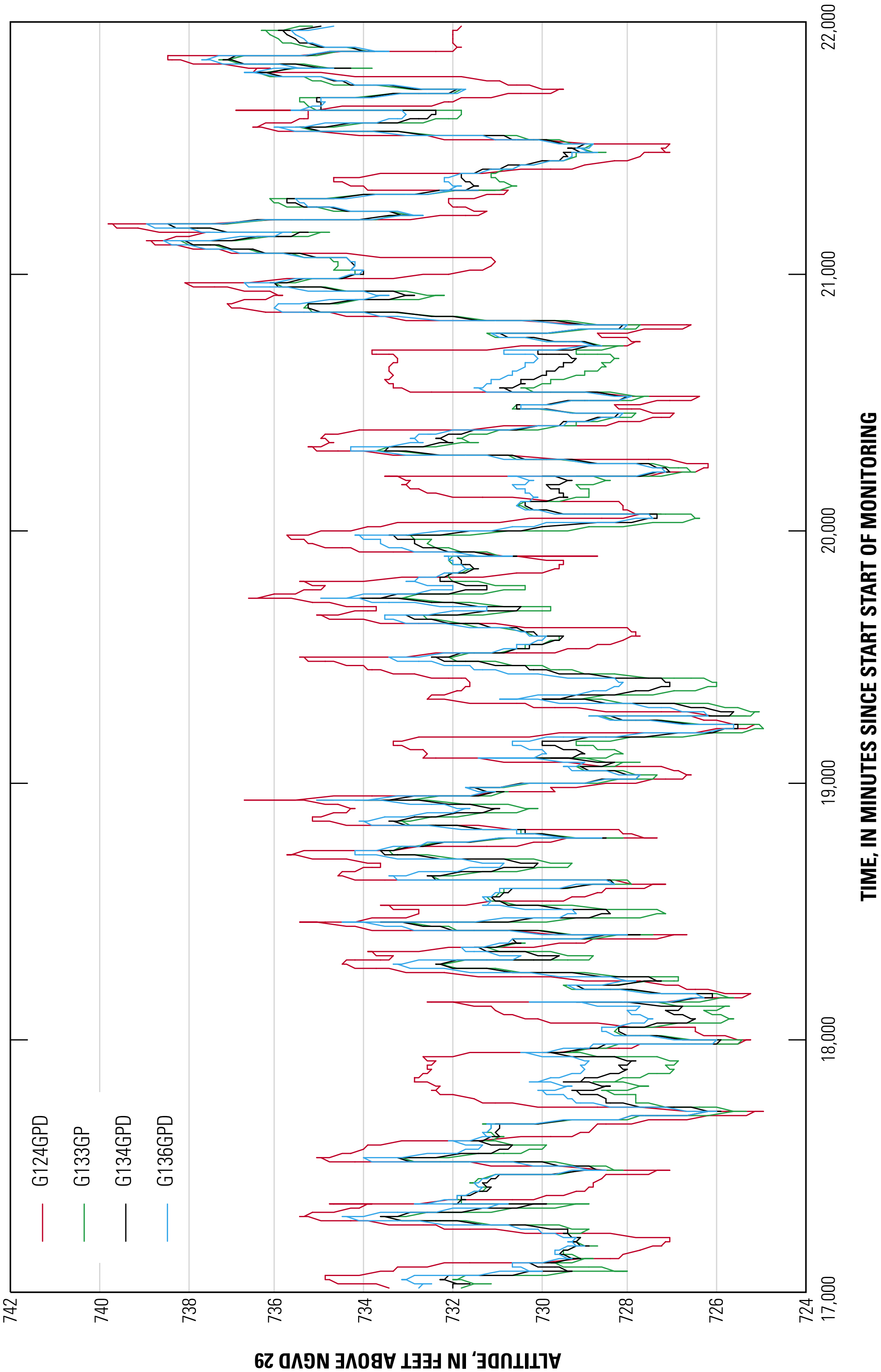


Figure F8. Water-level fluctuations in wells G124GP, G133GP, G134GP, and G136GP open to the 525-ft parting in Belvidere, Ill.

in recharge.

The timing of the water-level changes generally was similar at all depths of the aquifer (fig. F7b). These trends indicate that the Galena-Platteville aquifer has sufficient hydraulic connection to respond to ambient hydraulic effects as a single aquifer. However, as indicated by the continuous measurements, the upper part of the aquifer seemed to be partly hydraulically isolated from the deeper parts of the aquifer. The partial isolation is made apparent when the aquifer is pumped. For example, water-level measurements collected during June and October of 1991 in monitoring wells open to the Galena-Platteville aquifer at the PCHSS indicate that ground-water-flow directions differ between the upper (above 632 FANGVD29) and middle parts of the aquifer. Flow in the upper part of the aquifer is oriented to the southwest, whereas flow in the middle part of the aquifer is to the southeast (fig. F9). Furthermore, the direction of ground-water flow in the middle part of the aquifer at the PCHSS varied by about 15° between June and October, presumably in response to variations in the effects of pumping in the nearby municipal-supply wells. No variation in the direction of ground-water flow was detected in the upper part of the aquifer (Mills, 1993b). The difference in flow directions between the middle and upper parts of the Galena-Platteville aquifer indicate that these two parts of the aquifer have some hydraulic isolation, which indicates the presence of vertical variations in permeability within the aquifer.

Water levels also were measured periodically at clusters of vertically nested monitoring wells. Measurements were made at intervals from once per year to about monthly. These data provided information on vertical gradients within the Galena-Platteville aquifer and between it and the glacial drift and St. Peter aquifers above and below, respectively.

Vertical-hydraulic gradients between the glacial drift aquifer and the upper 30 ft of the Galena-Platte-

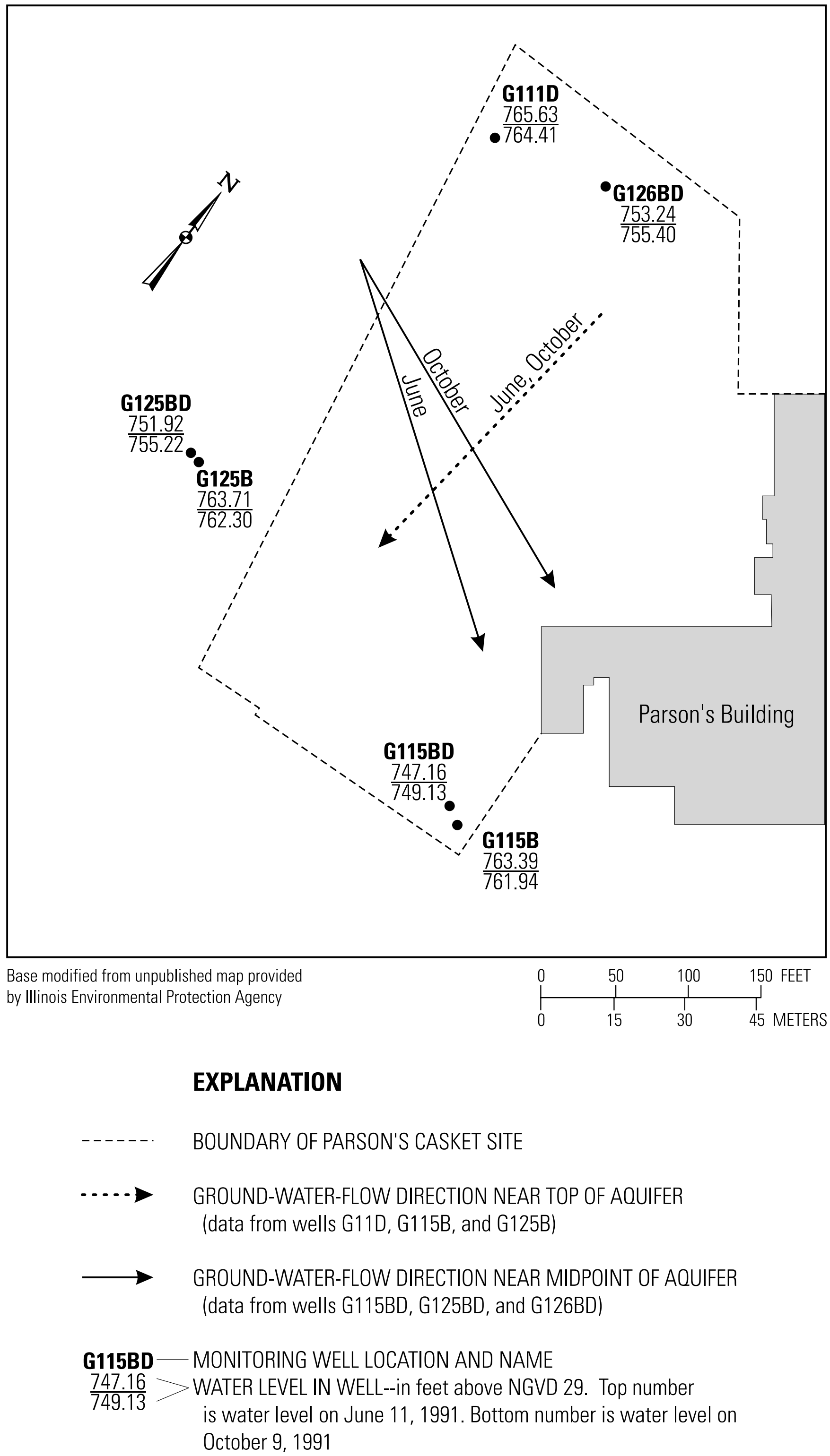


Figure F9. Water-level altitudes and approximate ground-water-flow directions in the Galena-Platteville aquifer, Belvidere, Ill., June and October 1991.

ville aquifer typically are directed downward away from streams. Supplemental data from the Belvidere Landfill No. 1 site (fig. 30) (Roy F. Weston, Inc., 1988) indicate that gradients are upward where flow discharges from the upper part of the aquifer into the Kishwaukee River (and likely to other streams).

In and near the city of Belvidere, vertical hydraulic gradients within the Galena-Platteville aquifer typically are downward away from streams. No data are available from the deeper part of the aquifer immediately adjacent to streams. However, water levels measured at well G436BD and boreholes B134GP and B137GP located within about 350 ft of the Kishwaukee River (fig. 30) indicate a downward gradient of about 0.05-0.1 ft/ft between the river and the deeper part of the aquifer. Flow in the deep part of the aquifer in these areas, particularly in the 525-ft parting, appears to move beneath the river to nearby municipal- and industrial-supply wells. These flow directions are at least partly in response to pumping from water-supply wells and may not represent natural conditions.

In the city of Belvidere and vicinity, vertical-hydraulic gradients between the Galena-Platteville and St. Peter aquifers appear to be directed downward under natural conditions, but flow directions may be reversed in the vicinity of the water-supply wells during pumping periods (fig. F7c). At the G127GP/G127SP well nest at the PCHSS, gradients typically range from about 0.13 ft/ft downward to 0.06 ft/ft upward (Mills and others, 1998).

Single measurements with packers

Single water-level measurements were collected in test intervals isolated with a dual-packer assembly in 18 boreholes in the Belvidere area, primarily in the vicinity of the PCHSS (Mills, 1993a, b, c; Mills and others, 1998; Mills and others, 2002a) (table 17). These water-level data improved understanding of the magnitude of the vertical variations in water level within the Galena-Platteville aquifer and the factors that affect these variations.

Vertical differences in water levels above and below the test intervals isolated with a dual-packer assembly typically varied with the borehole depth. Water levels above and below the test intervals in boreholes T1, T6, (table F4), T2, T3, T5, T7, T8, B125BD, and B126BD typically varied by less than 5 ft. Water levels above and below the test intervals in borehole B115BD typically varied by less than 5 ft and always varied by less than 11 ft, with the largest differences in the test intervals below 656 FANGVD29. These boreholes are drilled to a depth of 215 ft or less (altitude greater than about 570 FANGVD29) (table 18). Water levels above and below the test intervals in boreholes B124GP, B127GP, B128GP, B133GP, B134GP, B136GP, and B137GP varied as much as 30 ft (table F4). These boreholes are drilled to a depth in excess of 265 ft (altitude about 520 FANGVD29). Water levels measured in the test intervals open at or near the marker bed at about 660 FANGVD29 in boreholes B124GP, B133GP, and B136GP were within 2.5 ft of the water levels above the test interval, but were more than 14 ft higher than water levels below the test interval. The increase in differences in water levels with borehole depth is, in part, a response to the effects of pumping in the nearby water-supply wells and indicates that the vertical hydraulic conductivity of the Galena-Platteville aquifer decreases with depth. This decrease in permeability indicates that vertical secondary-permeability features in the Galena-Platteville aquifer are fewer, smaller, and less interconnected with depth at the PCHSS, and presumably the entire Belvidere area. The small difference in water levels within the Galena-Platteville aquifer above the marker bed at 660 FANGVD29 and the large difference in water levels below that altitude indicate that this bed may correspond to a transition from depths of higher to lower vertical hydraulic interconnection in at least some locations. This interpretation is consistent with the analysis of the cores and borehole GPR data.

Single water-level measurements from test intervals isolated with a packer assembly also were useful for identifying permeable intervals in the aquifer at boreholes T1-T8 at the PCHSS. Data from borehole T6 are representative of boreholes T5-T8. Water levels in borehole T6 prior to packer inflation typically were within 0.05 ft of the water level in the zone (either within or above the test interval) that was open to the subhorizontal bedding-plane parting at about 744 FANGVD29 (fig. F2, table F4). Water levels in the zones not open to this bedding-plane parting (within or below the test interval) typically were 0.5-3 ft lower than in the open borehole. The water-level measurements indicate that the subhorizontal bedding-plane parting at about 744 FANGVD29 in boreholes T5-T8 is the most permeable feature at these boreholes. Water-level measurements also indicate that the inclined fracture at about 699-709 FANGVD29 in boreholes T1 and T2 may be the most permeable feature in these boreholes (tables 20, F4).

Geophysical logs

Various geophysical logs were run in boreholes and wells open to the Galena-Platteville aquifer as part of the Belvidere area study (table 17). The boreholes were distributed across an area of about 1.5 mi^2 in Belvidere, but most were near the PCHSS. Many of the logs were useful in enhancing characterization of the hydrologic framework of the area.

Spontaneous potential

SP logging was done in eight boreholes and one well (table 17). SP logs indicated abrupt increases in signal response at about 660 FANGVD29 in borehole B125BD; about 660, 673, 705, and 755 FANGVD29 in borehole B126BD; 525 and 660 FANGVD29 in borehole B127GP (fig. F3); and about 485 and 660 FANGVD29 in borehole B127SP, and, possibly, at about 500 and 525 FANGVD29 in borehole B128GP (fig. F1). These intervals correspond to lithologic contacts, particularly the 525- and 660-ft partings, that may correspond to permeable features in the Galena-Platteville aquifer. Gradual increase in spontaneous potential was detected above about 660 FANGVD29 in boreholes B125GP, B126GP, and B127GP. This interval also may correspond to permeable features in the aquifer. SP logs run in boreholes B115BD, B436, B305, and B137GP did not indicate the presence of permeable features.

Bedding-plane partings associated with argillaceous deposits at about 525 and 660 FANGVD29 may be permeable based on interpretations of the SP logs. SP response also appears to be affected by clay content and changes in borehole diameter, such as the large increase in SP response at 485 FANGVD29 in borehole B127SP, an altitude where there is no apparent fracture or increase in natural-gamma activity, but with a decreased borehole diameter. It is unclear, therefore, if the SP log is responding to geologic or hydraulic conditions. The utility of the SP log is decreased by its poor resolution of the depth of the secondary-permeability feature as defined with other methods. For example, the SP signal response to the feature at 525 FANGVD29 in borehole B127GP (fig. F3) occurs over a range of about 5 ft. Use of the SPR log may assist the interpretation of SP logs. At all depths where partings are indicated in both the SP and SPR logs, the signal responses are opposite (increase in SP log and decrease in SPR signal). At 485

Table F4. Water levels in test intervals isolated with a packer assembly from select boreholes, Belvidere, Ill.

[NA, not available; NT, measurement not taken; < less than]

Borehole name (fig. 31)	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Altitude of water level			
		Open borehole (feet above National Geodetic Vertical Datum of 1929)	Above test interval (feet above National Geodetic Vertical Datum of 1929)	In test interval (feet above National Geodetic Vertical Datum of 1929)	Below test interval (feet above National Geodetic Vertical Datum of 1929)
T1	567-582	759.50	757.88	755.42	NA
	616-626	760.89	760.95	757.80	757.12
	627-637	760.98	761.00	759.94	759.47
	696-733	760.86	NA	760.97	758.27
T6	579-589	760.67	760.77	757.25	757.40
	589-599	760.74	760.78	757.92	758.01
	606-616	760.68	760.74	759.15	757.66
	616-626	760.73	760.72	759.42	757.98
	627-637	760.81	760.75	756.44	755.25
	682-692	761.47	761.48	760.50	759.17
	742-745	760.66	NA	760.70	758.46
B124GP	518-540	NT	758.95	731.55	NA
	556-566	NT	758.11	752.51	731.49
	658-668	747.25	760.38	758.40	743.87
	716-747	NT	NA	748.68	745.87
	737-747	742.75	NA	757.03	<754
B115BD	631-646	NT	762.96	753.20	NA
	646-656	NT	762.88	757.30	754.58
	656-666	NT	762.95	761.95	754.84
	666-676	NT	762.92	761.44	761.08
	676-686	NT	762.97	761.70	760.96
	686-696	NT	762.93	761.81	760.93
	696-706	NT	762.86	762.23	760.96
	710-720	NT	763.79	763.66	763.00
	724-734	NT	763.62	763.50	792.96
	742-745	NT	NA	763.59	762.76

FANGVD29, the altitude of the increase in SP signal in borehole B127SP, the SPR signal also increases. Where natural-gamma and caliper logs are unavailable, this similarity in response may be useful in distinguishing changes in diameter resulting from drilling or from hydraulic features.

Temperature

Temperature logging was done in 12 boreholes and 1 well (table 17). Temperature logs typically indicated an overall decrease in water temperature with increasing depth, with particularly large changes across the first 5-10 ft of the water column. Temperature changes in the upper part of the water column likely reflect the effect of ambient temperature on the water and the probe, and not the presence of permeable features. Abrupt changes in fluid temperature were observed at about 525, 560, and 728 FANGVD29 in borehole B124GP (fig. F4); at about 525 FANGVD29 in borehole B127GP (fig. F3); at about 483 and 565 FANGVD29 in borehole B128GP (fig. F1); at about 521 FANGVD29 in borehole B133GP; at about 525 FANGVD29 in boreholes B134GP and B136GP (fig. F6); and at about 525, 647, and 703 FANGVD29 in borehole B137GP. Many of these intervals correspond to bedding-plane partings identified with other methods and may be permeable (tables F1, 20). Changes in the rate of change in fluid temperature with depth were observed at about 660 FANGVD29 in borehole B134GP, and about 525 and above 702 FANGVD29 in borehole B127GP. These intervals also may correspond to the locations of permeable features in the aquifer (table 20).

Fluid resistivity

Fluid-resistivity logging was done in 11 boreholes and 1 well (table 17). For the most part, resistivity measurements did not vary except near the top of the water column within the borehole casings. Resistivity logs did indicate moderate to abrupt changes in signal response at about 563 and 728 FANGVD29 in borehole B124GP (fig. F4), at about 525 and 565 FANGVD29 in borehole B128GP, at about 743 FANGVD29 in borehole B130GP (fig. F5), at about 525, 660, and 720 FANGVD29 in borehole B133GP, at about 683 FANGVD29 in borehole B134GP, and at about 525 and 725 FANGVD29 in borehole B136GP (fig. F6), and between about 655 and 665 FANGVD29 in borehole B436. Many of these intervals correspond to bedding-plane partings and appear to be permeable (table 20). Fluid-resistivity logs from the remaining boreholes indicated no changes in resistivity that clearly would be indicative of permeable features.

Heat-pulse flowmeter logs

Flowmeter logs were run under hydraulic conditions of ambient flow in 16 boreholes and well BMW2 (table 17). Flow typically was directed downward in these boreholes, with intermittent measurement of upward flow apparently being related to the pumping effects from nearby water-supply wells.

Flowmeter logging in borehole B124GP indicates inflow from bedding-plane partings and vugs from the bottom of the borehole casing to the top of the 660-ft parting, inflow from a subhorizontal bedding-plane parting at about 564 FANGVD29, and outflow through the 525-ft parting (fig. F4). Flow volumes in borehole B127GP varied during different logging events for that part of the borehole above 525 FANGVD29, indicating possible inflow from bedding-plane partings or vugs at about 705-725 FANGVD29 and through the 660-ft parting (fig. F3). Flowmeter logging clearly indicated outflow through the 525-ft parting in borehole B127GP. Although predominantly downward, upward flow in the borehole also was recorded. The variability in the amount and direction of flow in borehole B127GP is in apparent response to pumping from wells BMW4 and BMW6. Flowmeter logging in borehole B128GP indicates flow through the 485-, 525-, and 660-ft partings (fig. F1). Flowmeter logs run in borehole B130GP indicate inflow from a subhorizontal bedding-plane parting below the bottom of the casing at about 746 FANGVD29 and outflow through a subhorizontal bedding-plane parting at about 567 FANGVD29 (fig. F5). Flowmeter logs in boreholes B133GP, B134GP, and B136GP (fig. F6) indicate inflow through bedding-plane partings and vugs from the bottom of the casing to the 660-ft parting, and outflow through the 525-ft parting. Flowmeter logging in borehole B137GP indicates inflow below the bottom of the casing at about 724 FANGVD29, outflow through subhorizontal bedding-plane partings and vugs between about 648 and 724 FANGVD29, and outflow through subhorizontal bedding-plane partings at about 577 and 525 FANGVD29.

Flowmeter logging done under ambient-flow conditions in boreholes T1-T8 indicated variable flow directions during different logging events. Downward flow was measured above 604 FANGVD29 during all logging events. Between about 584 and 604 FANGVD29, upward and downward flow was measured in boreholes T1 (fig. A3), T2, T3, T6 (fig. F2), and T7 during at least one of the three logging events in these boreholes. The transition between upward and downward flow and the transient nature of the change indicates a permeable feature may be present between 584 and 604 FANGVD29, and that this feature is in better hydraulic connection with the secondary-permeability network affected by pumping in the municipal wells than the rest of the borehole. However, analysis of the lithologic and geophysical logs did not identify a secondary-permeability feature in this interval. Flowmeter logging in boreholes T1 and T2 indicates inflow associated with the high-angle fracture between about 699 and 709 FANGVD29, and outflow through the vugs between about 602 and 642 FANGVD29 (fig. A3). Flowmeter logging in borehole T3 indicates inflow through vugs between about 684 and 694 FANGVD29, and outflow through vugs between 632 and 642 FANGVD29. Flowmeter logging in borehole T5 indicates inflow associated with a subhorizontal bedding-plane parting at about 742 FANGVD29, and outflow through vugs between about 682 and 692 FANGVD29. Flowmeter logging in boreholes T6, T7, and T8 indicates inflow associated with a subhorizontal bedding-plane parting at about 742 FANGVD29, and outflow through vugs between about 682 and 692 and 589 and 647 FANGVD29 (fig. F2).

Flowmeter logging in municipal well BMW2 was limited to one flow measurement (at about 590 FANGVD29) within the interval open to the Galena-Platteville aquifer because of concerns over tool safety. About 5 gal/min of downward flow at this point indicated inflow from bedding-plane partings above 590 FANGVD29, potentially including the 660-ft parting, and (or) a steeply inclined fracture at an altitude of about 625 FANGVD29 (depth of about 135 ft).

Downward flow also was recorded during logging of borehole B436. Inflow occurred from the weathered surface of the Galena-Platteville aquifer, just below the base of the casing at altitude of about 735 FANGVD29 (depth about 30 ft), and from the 660-ft parting. Inflow was recorded at an altitude of about 620 FANGVD29 (depth about 145 ft), however, no partings or fractures are evident in the geophysical logs at this interval. Vugs are identified in the acoustic-televiewer log, however, their size and prevalence appear much greater in other intervals where inflow was not recorded.

Flowmeter Logging During In-Borehole Pumping

Flowmeter logging in conjunction with pumping in boreholes B124GP, B133GP, B134GP, and B136GP identified the same permeable features that were identified during logging under ambient-flow conditions (figs. F4, F6). Logging in conjunction with pumping tended to emphasize the flow contribution from the permeable features above 660 FANGVD29, but the volume of flow below 660 FANGVD29 typically was similar to the volume measured under ambient conditions. Differences between the ambient and in-borehole pumping profiles above 660 FANGVD29 indicate that vertical hydraulic gradients are smaller above than below 660 FANGVD29, and flow rates are affected by drawdown induced by pumping. The small differences between the ambient and pumping profiles below 660 FANGVD29 indicate that pumping had little effect on flow, which indicates that the vertical hydraulic gradients below this interval are high, and that the vertical hydraulic conductivity of this interval is low in comparison to that above 660 FANGVD29. These results are consistent with the analysis of the water-level data collected by use of a packer assembly in these boreholes.

Logging During Cross-Borehole Pumping

While boreholes T1, T3, and T7 were pumped as part of their development, flowmeter logs were run in the other boreholes in the T1-T8 series. Analysis of flowmeter data collected during this logging identified four permeable features in that part of the Galena-Platteville aquifer penetrated by these boreholes: (1) the subhorizontal bedding-plane parting at about 742 FANGVD29 in boreholes T5, T6, T7, and T8; (2) the inclined fracture from 699 to 709 FANGVD29 at boreholes T1 and T2; (3) vugs from about 682 to 692 FANGVD29; and (4) vugs from about 602 to 642 FANGVD29. These features are consistent with those identified with the flowmeter logging under ambient conditions in these boreholes, and to a lesser degree with the lithologic logging. Logging during pumping tended to emphasize the location of the permeable features and to highlight their interconnection.

Based on the flowmeter data collected during both ambient and cross-borehole pumping, Paillet (1997) calculated the transmissivity of the subhorizontal bedding-plane parting at about 742 FANGVD29 to be 216 ft^2/d, with a storage coefficient of less than 1×10^{-3} (table F5). The transmissivity of the inclined fracture from 697 to 707 FANGVD29 was calculated to be 130 ft^2/d, with an undetermined storage coefficient. The transmissivity of the vuggy interval from 682 to 692 FANGVD29 was calculated to be 8.6 ft^2/d, with a storage coefficient of 2×10^{-5}. The transmissivity and storage coefficient of the vuggy interval at about 602-642 FANGVD29 were calculated to be 43 ft^2/d and 2×10^{-5}, respectively.

Aquifer tests

Slug tests, specific-capacity tests, multiple-well aquifer tests, and tracer tests were performed in the Galena-Platteville aquifer in the Belvidere area.

Slug tests

Kh values were obtained from slug tests in monitoring wells and in test intervals isolated with a packer assembly (table 17). All test locations were in the Belvidere area, and about two-thirds of the locations at or near the PCHSS. Tests in wells done as part of other studies (Clayton Environmental Consultants, Inc., 1996; GZA GeoEnvironmental, Inc., 1993; Roy F. Weston, Inc., 1988) also were evaluated. About 90 percent of the aquifer thickness was tested in 51 test intervals isolated with a packer assembly at 5 boreholes. Additional tests were performed in 87 selected test intervals isolated with a packer assembly in 15 boreholes.

Kh values from slug tests in the Galena-Platteville aquifer ranged from about 0.005 to about 2,500 ft/d. This large variation in Kh indicates that the Galena-Platteville aquifer is highly heterogeneous in the Belvidere area. Intervals with elevated Kh (greater than 1 ft/d) were restricted primarily to four parts of the aquifer: the upper 20 ft of the bedrock, the 660-ft parting, the 564-parting, and the 525-ft parting (fig. 35). Elevated Kh values for these intervals were not recorded at all locations and in at least one borehole, B128GP, additional partings with elevated Kh compared to the rest of the aquifer (at altitudes of about 595 and 485 FANGVD29; depths of about 190 and 300 ft) were recorded (fig. F1).

On the basis of vertical variations in Kh, and in conjunction with interpretations based on other methods, the Galena-Platteville aquifer within the Belvidere area can be divided arbitrarily into five units: the upper 20 ft of the bedrock surface, from 21 ft below the bedrock surface to the 660-ft parting, from below the 660-ft parting to just above the 525-ft parting, the 525-ft parting, and from the bottom of the 525-ft parting to the base of the aquifer at about 455 FANGVD29. These units are recognized primarily from data at and near the PCHSS and their presence may differ within the Belvidere area.

Table F5. Aquifer parameters calculated from flowmeter logging, slug testing, and constant-discharge aquifer testing for select boreholes, Belvidere, Ill.

[< less than; na, not applicable; nc, not calculated]

	Cross-borehole flowmeter logging			Slug testing			Constant-discharge aquifer testing		
Permeable feature	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)
Subhorizontal fracture at about 742 feet in boreholes T5, T6, T7, and T8	216	<0.001	na	516	na	71.6	7414	0.02	na
Inclined fracture from about 699 to 709 feet in boreholes T1 and T2	130	na	na	1900	na	na	22.6	.00076	na
Vuggy interval from about 682 to 692 feet in boreholes T1 through T8	8.6	.00002	0.9	5.6	na	.56	nc	nc	nc
Vuggy interval from about 602 to 642 feet in boreholes T1 through T8	42.3	.00002	1.1	18.2	na	.91	18.1	na	1.6

For example, a semiconfining unit was identified above the 660-ft parting near an industrial facility about 2.5 mi southwest of the PCHSS (GZA GeoEnvironmental, Inc., 1993). However, data review indicates that this semiconfining unit may be the clay-rich interval associated with the 660-ft parting.

Kh values obtained from 13 slug tests done in the upper 20 ft of the Galena-Platteville aquifer ranged from 0.054 to 360 ft/d with a geometric mean of 4.3 ft/d. These values indicate that the upper 20 ft of the aquifer generally is permeable and contains a well-developed network of interconnected secondary-permeability features.

Kh values obtained from 29 slug tests done in that part of the aquifer from 21 ft below the bedrock surface to the 660-ft parting ranged from 0.067 to 2,500 ft/d, with the highest values being associated with the 660-ft parting. Excluding the outlier value of 2,500 ft/d, the geometric mean Kh for this part of the aquifer is 0.36 ft/d. Kh values from 31 slug tests done in the Galena-Platteville aquifer between the 660- and 525-ft partings, and excluding an anomalous permeable parting at 564-ft identified in various boreholes, ranged from 0.036 to 20 ft/d, with a geometric mean of 0.37 ft/d. Kh values obtained from analysis of four slug tests done in the 564-ft parting ranged from 0.036 to 21 ft/d with a mean value of 2.4 ft/d. These values indicate that with the exception of the 564- and 660-ft partings, which vary in permeability, this interval is only moderately permeable in the Belvidere area.

Kh values obtained from analysis of six slug tests of the 525-ft parting ranged from 0.13 to 180 ft/d with a geometric mean value of 17.3 ft/d. Typically, this feature is highly permeable in the Belvidere area.

Kh values obtained from analysis of seven slug tests done below the 525-ft parting ranged from 0.005 to 11 ft/d with a geometric mean of 0.21 ft/d. Typically, this part of the aquifer is moderately to poorly permeable in the Belvidere area.

Kh values obtained from analysis of the slug tests also were evaluated in relation to the stratigraphic units to which the wells or borehole-test intervals were open (fig. F10). The highest geometric mean and greatest range of Kh for these units is associated with the Dubuque/Wise Lake Formations of the Galena Group and the Grand Detour Formation of the Platteville Group (excluding the Quimbys Mill Formation, where too few tests were available for evaluation). This distribution results, at least in part, because of the high permeability of the weathered-bedrock surface and the 660-ft parting located in the Dubuque and Wise Lake Formations and the 525-ft parting located in the Grand Detour Formation (figs. 35, F1, F4, F6).

The location of permeable features identified from the slug tests frequently indicated good agreement with the location of permeable features identified with lithologic and geophysical logging, and water-level measurements (table 20). This agreement partly is related in that many of the intervals chosen for slug-testing were selected because flowmeter logging indicated the presence of permeable features. Areas of elevated permeability identified with multiple methods include the shallow subhorizontal bedding-plane parting at about 742 FANGVD29 in boreholes T5-T8, the high-angle fracture at about 699-709 FANGVD29 in boreholes T1 and T2, and the 525-ft and 660-ft parting in many boreholes (figs. 35, A3, F1, F2, F4-F6; table 20). However, areas of active flow identified in the vuggy intervals at 602-642 and 682-692 in boreholes T1-T8 and above 662 FANGVD29 in boreholes B124GP, B126GP, B127GP, B133GP, B134GP, and B136GP frequently had Kh values of less than 0.50 ft/d, whereas the 658-668 FANGVD29 interval in borehole B130GP had a Kh value of about 1.0 ft/d, but was not identified as being permeable with any other method. In borehole B128GP, slug tests indicated Kh values of 17 and 48 ft/d at about 564 and 595 FANGVD29 (depths about 190 and 220 ft), respectively, yet flowmeter logging indicated no flow at these altitudes. These occasional differences between slug testing and flow profiling appear to be caused by the distribution of variations in vertical hydraulic gradient and Kh within the individual boreholes. At boreholes T1 and T6, highly permeable features are present only near the top of the boreholes (figs. A3, F2). Under these conditions, water coming in through the fractures in the upper part of the boreholes only can move out through the less permeable features in the deeper part of the borehole, which can be identified with the flowmeter logging. At borehole B128GP (fig. F1), permeable features are distributed over the length of the borehole, with the largest differences in water level being between the top and bottom of the borehole. Under these conditions, most inflow is from the permeable features at the top of the borehole, most outflow is through the 525-ft parting near the bottom of the borehole, and less permeable features in the middle of the borehole (such as the parting at about 565 FANGVD29 with Kh of 17 ft/d) may not affect the water movement. Such permeable features may not be identified with flowmeter logging, but they can be identified with slug tests.

Differences in the location of permeable features identified with slug tests and some of the other study methods also may be the result of nearby pumping. During tests in the deeper part of the Galena-Platteville aquifer, water levels usually fluctuated and the data could not be analyzed. The effect was most evident in test intervals open to the permeable 660-ft and 525-ft partings. For example, analysis of slug testing done on the 660-ft parting at borehole B115BD yielded Kh values that varied by two orders of magnitude potentially because of pumping effects. Pumping affected the calculated of Kh in borehole B127GP, resulting in the lowest value reported for the 525-ft parting (0.13 ft/d). However, flowmeter logging indicated that the 525-ft parting was permeable at this borehole.

The vertical distribution of permeability within the Galena-Platteville aquifer identified from the slug tests indicated moderate agreement with the distribution identified with the continuous water-level measurements (table 20). Results from application of both methods indicated that the 525-ft parting was permeable. However, water-level measurements, core analysis, and single-hole GPR surveys indicated a decrease in aquifer permeability with depth, whereas slug tests did not indicate substantial changes in the Kh of the aquifer, which were not associated with bedding-plane partings and the weathered bedrock. These differences likely are related to the importance of the vertical secondary-permeability features on flow in the aquifer. These features were underrepresented by the small amount of aquifer stressed by slug testing in the vertical boreholes, but were well represented in the large volume of aquifer (thousands of cubic feet) stressed by the municipal-well pumping.

Specific-Capacity Tests

Spatial variability in transmissivity and Kh of the Galena-Platteville aquifer was computed from specific-capacity data recorded on the driller's logs of about 250 residential-supply wells open to the aquifer (table 17).

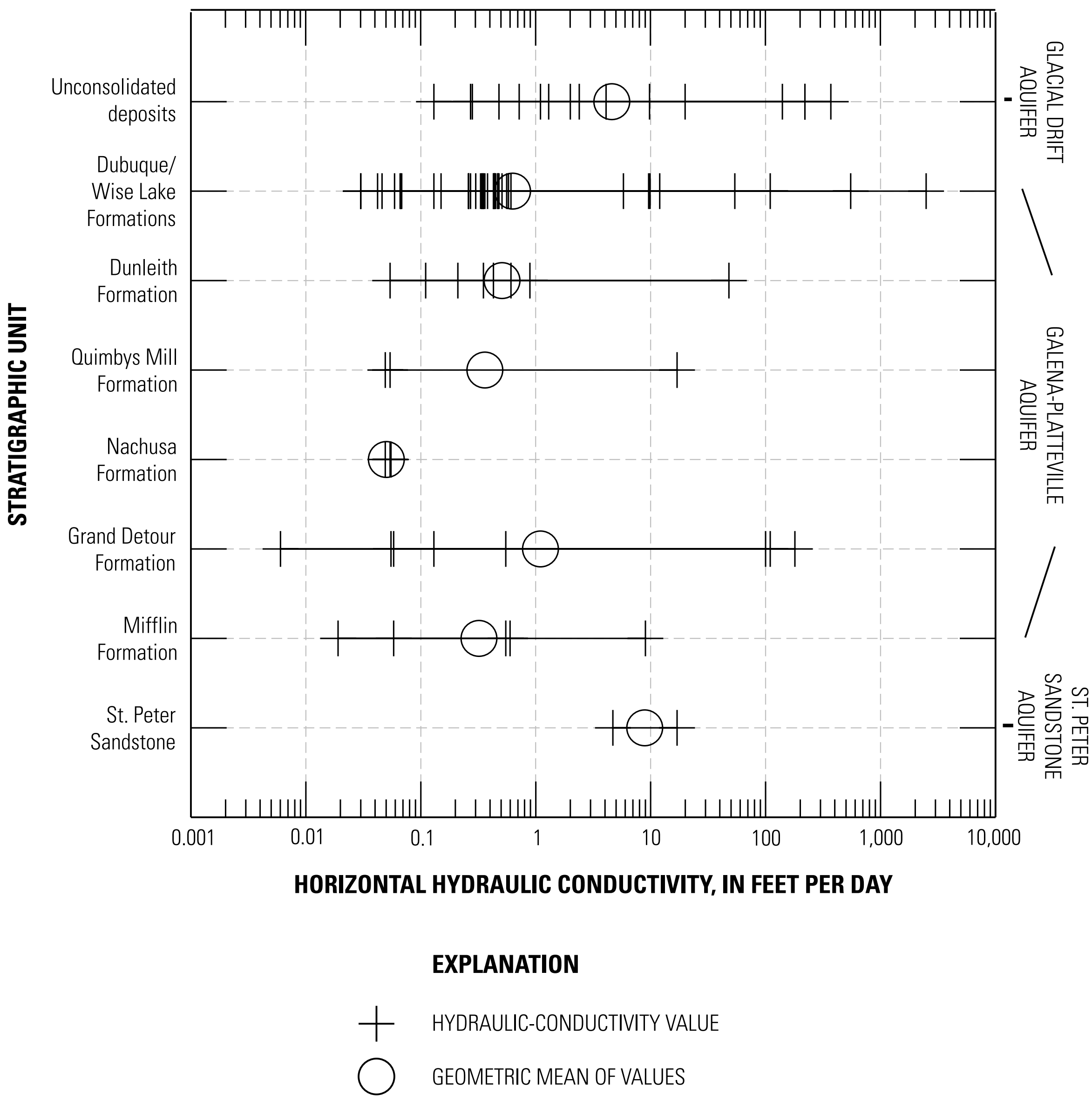


Figure F10. Distribution of horizontal hydraulic conductivity within units that compose the Glacial Drift, Galena-Platteville, and St. Peter aquifers underlying Belvidere, Ill.

The wells were distributed throughout the Belvidere area, but about 90 percent of the wells tested were from four rural subdivisions. About 75 percent of the wells were open only to the upper part of the aquifer. Specific-capacity data collected during development of boreholes B130GP, B133GP, B134GP, and B136GP near the PCHSS also were analyzed. These boreholes penetrated more than 75 percent of the aquifer.

Estimated transmissivity and Kh values indicated no clear variations with location or amount of aquifer penetrated. Transmissivity estimates from the residential-supply wells ranged from about 30 to 7,700 ft^2/d; with about 90 percent of the wells being less than 1,000 ft^2/d. Estimated Kh from these wells ranged from about 0.2 to 450 ft/d; in 98 percent of the wells, Kh was less than 50 ft/d. Transmissivity estimates from boreholes B130GP, B133GP, B134GP, and B136GP were 5,400 ft^2/d, 430 ft^2/d, 270 ft^2/d, and 1,100 ft^2/d, respectively. Kh estimates from these boreholes ranged from 1.3 to 29 ft/d.

Multiple-Well, Constant-Discharge Tests

A multiple-well, constant-discharge aquifer test was done in June 1991 by pumping 29 gal/min from borehole B127GP over a period of 1,020 minutes (Mills, 1993b). Borehole B127GP penetrated about 90 percent of the thickness of the Galena-Platteville aquifer during this test. Drawdown was measured in monitoring wells G115B, G125B, and G111D open to the upper 10-20 ft of the aquifer and monitoring wells G115BD, G125BD, and G126BD open to the aquifer above about 635 FANGVD29 (fig. F11). Interpretation of the aquifer-test data are complicated by changes in water levels because of pumping from wells BMW4 and BMW6, the proximity of the shallow wells to the overlying glacial drift aquifer, and a lack of observation wells (only three observation wells each in the middle and shallow parts of the aquifer).

Drawdown in wells G115B, G125B, and G111D ranged from 0.01 to 0.37 ft and the cone of depression was oriented approximately N. 45° W./S. 45° E. (fig. F11). Drawdown in wells G115BD, G125BD, and G126BD ranged from 0.76 to 4.29 ft, and was oriented approximately east-west. These orientations are based on only three data points in each part of the aquifer and should be considered as approximate. The drawdown orientation in both the shallow and deep parts of the aquifer is consistent with either the primary or secondary orientation of inclined fractures identified with the SAR survey in this area as well as the predominate fracture orientation identified with the single-hole GPR tomography in borehole B127GP. The difference in the orientation of drawdown indicates that there may be a change in the dominant orientation of the inclined fractures with depth in the aquifer, which is consistent with the SAR survey.

Transmissivity estimates ranged from about 150 to 300 ft^2/d for the deep (100-200 ft) part of the aquifer and from about 1,500 to 7,000 ft^2/d for the shallow (40-100 ft) part of the aquifer using the method of Boulton and Streltsova-Adams (1978). Kh estimates for these respective parts of the aquifer ranged from 0.6 to 1.0 ft/d and from about 5 to 30 ft/d. Specific yield based on data from well G125BD was about 0.2. Kh values estimated from the constant-discharge test for the deeper part of the aquifer at borehole B127GP were higher, but generally consistent with those obtained from slug tests done in seven test intervals isolated with a packer assembly in the deeper part of this borehole (average value of 0.22 ft/d). Slug tests were not performed in the upper part of this borehole, so comparisons between the shallower and deeper parts of the aquifer cannot be made.

A series of constant-discharge aquifer tests was done to test the hydraulic properties of the permeable intervals in the Galena-Platteville aquifer identified at boreholes T1-T8. Packers were used to isolate selected parts of boreholes T1, T2, T3, T5, T6, T7, and T8 in addition to monitoring well G115BD (table F6) so that the distribution of drawdown in the various parts of the aquifer could be measured. Borehole T1 was pumped to test the hydraulic properties of the upper and lower parts of the permeable vuggy interval identified with cross-borehole flowmeter logging at 618-638 FANGVD29 in boreholes T1-T8 and the inclined fracture identified at about 699-709 FANGVD29 in boreholes T1 and T2. Borehole T6 was pumped to test the hydraulic properties of the permeable subhorizontal bedding-plane parting identified at about 742 FANGVD29.

Analysis of the constant-discharge aquifer test done in the vuggy interval at 618-628 FANGVD29 indicated a transmissivity from about 8 to 22 ft^2/d and a Kh from 0.8 to 2.2 ft/d (table F5). Drawdown in the aquifer below 618 FANGVD29 typically was about 10 ft (table F6), indicating high vertical hydraulic connection between the vuggy interval and that part of the aquifer below 618 FANGVD29. Drawdown in the aquifer above 628 FANGVD29 was highest at borehole T3, which does not intercept permeable fractures, medium in boreholes T1 and T2, which are open to the permeable inclined fracture at about 699-709 FANGVD29, and lowest in boreholes T6-T8, which are open to the permeable subhorizontal bedding-plane parting at about 742 FANGVD29. The distribution of drawdown in these boreholes indicates vertical hydraulic connection between aquifer materials at 618-628 and above 628 FANGVD29, at least partly through inclined fractures.

Analysis of the constant-discharge aquifer test done in the vuggy interval at 628-638 FANGVD29 indicated a transmissivity from about 9 to 18 ft^2/d and a Kh from 0.9 to 1.8 ft/d (table F5). Drawdown in the aquifer below

628 FANGVD29 typically was about 10 ft, indicating high vertical hydraulic connection between the 628-638 interval and that part of the aquifer from about 567 to 624 FANGVD29 (table F6). Drawdown patterns in those parts of the aquifer open above 638 FANGVD29 were similar to those observed during the test of the interval at 618-628 FANGVD29.

Analysis of the constant-discharge aquifer test done in the inclined fracture at about 699-709 FANGVD29 in boreholes T1 and T2 indicated a transmissivity of 22 ft^2/d and a storage coefficient of 7.6 X 10^{-4} (table F5). A Kh was not calculated for this interval because of the uncertainty of the fracture aperture. About 1-1.5 ft of drawdown was detected in the aquifer below 699 FANGVD29 (table F6), indicating that this inclined fracture extends into the deeper part of the aquifer.

Analysis of the constant-discharge aquifer test done in the subhorizontal bedding-plane parting at about 742 FANGVD29 at borehole T6 indicated a transmissivity of more than 7,400 ft^2/d and a storage coefficient of 2.0 X 10^{-2} (table F5). A Kh was not calculated for this interval because of the uncertainty of the aperture of the bedding-plane parting. Little or no drawdown was measured in the aquifer below the bedding-plane parting. However, because drawdown in the subhorizontal bedding-plane parting was less than 0.30 ft, it is unclear if the absence of substantial drawdown in the deeper test intervals indicates minimal hydraulic interconnection between the bedding-plane parting and the aquifer below the parting, or that this part of the aquifer is permeable enough to respond easily to the small stress induced by pumping with minimal drawdown.

The hydraulic properties calculated from the constant-discharge aquifer tests in the T series of boreholes are similar to those calculated from the slug testing and analysis of flowmeter data collected during cross-hole pumping for the vuggy interval at 618-638 FANGVD29 (table F5). The

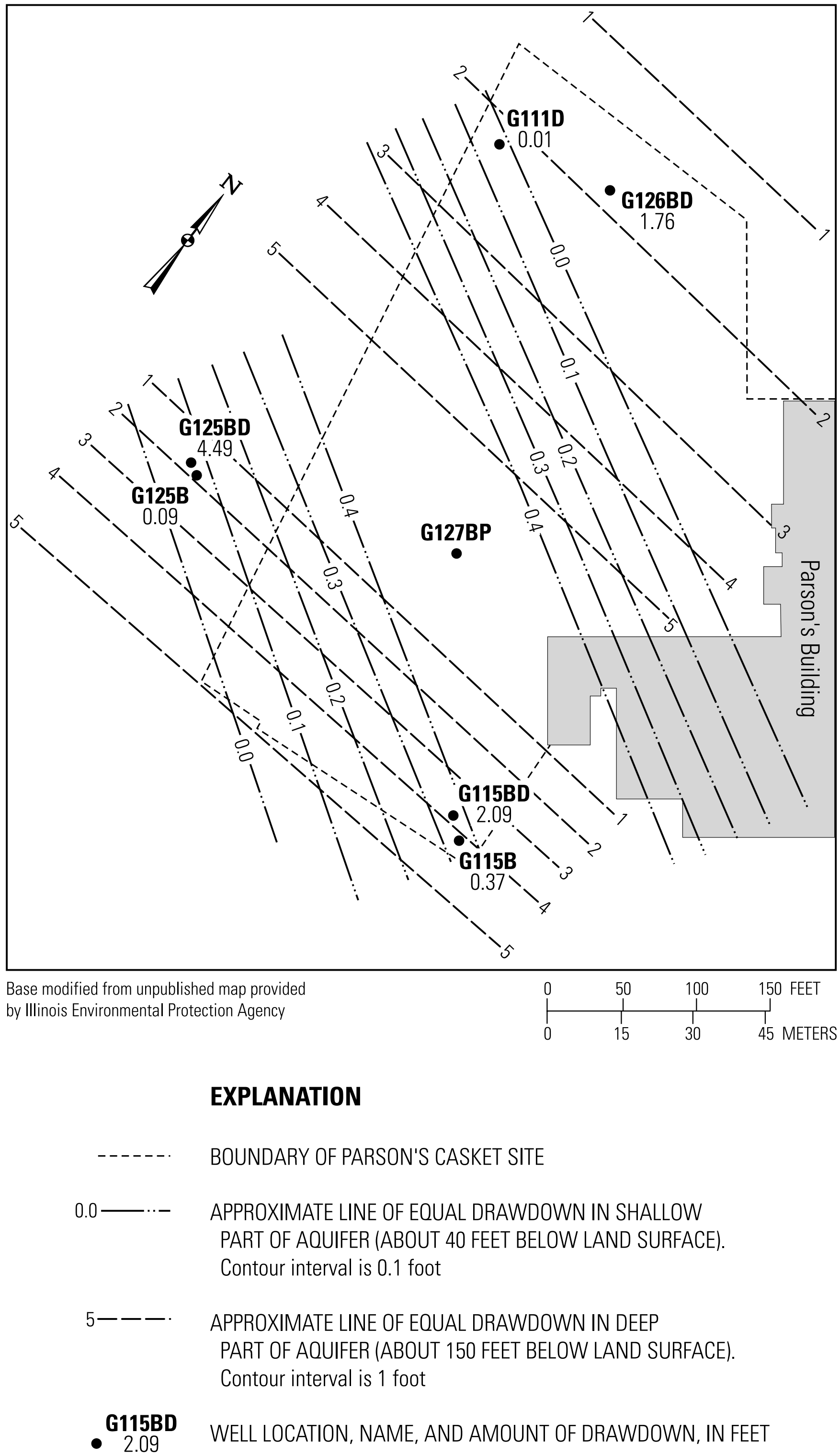


Figure F11. Differential drawdown in the upper and lower parts of the Galena-Platteville aquifer in response to a constant-discharge aquifer test, Belvidere, Ill., June 1991.

transmissivity calculated from the constant-discharge aquifer test in the T series of boreholes also is similar to that calculated from the flowmeter data collected during cross-hole pumping for the inclined fracture at 699-709 FANGVD29 at boreholes T1 and T2, but substantially is lower than the transmissivity value calculated with the slug testing. The hydraulic properties of the permeable intervals calculated from the constant-discharge aquifer tests in the T series of boreholes differ substantially from the hydraulic properties identified with the slug testing and flowmeter-data analysis for the subhorizontal bedding-plane parting at 742 FANGVD29 (table F5). This difference may partly result because of the volume of aquifer tested with the different methods. The inclined fracture appears to decrease in size and permeability with depth. Slug tests only stress the shallow, most permeable part of the fracture. The other methods involve pumping and also stress the deeper, less permeable parts of the fracture. The difference in the results of the test methods also may be because of the methods used in the

Table F6. Configuration of packers and distribution of drawdown during constant-discharge aquifer testing in boreholes T1-T8, Belvidere, Ill.

[>, greater than; na, not applicable]

			Packer configuration			Drawdown at end of test		
Pumped borehole	Altitude of pumped interval (feet above National Geodetic Vertical Datum of 1929)	Observation borehole	Altitude above packed interval (feet above National Geodetic Vertical Datum of 1929)	Altitude of packed interval (feet above National Geodetic Vertical Datum of 1929)	Altitude below packed interval (feet above National Geodetic Vertical Datum of 1929)	Above packed interval (feet)	In packed interval (feet)	Below packed interval (feet)
T1	616-626		630-732	616-626	567-612	0.57	63.51	11.62
		T2	630-734	616-626	567-612	.57	36.64	12.67
		T3	630-732	616-626	567-612	1.63	18.88	11.93
		T5	670-744	656-666	638-652	.06	.45	2.85
		T6	630-745	616-626	567-612	.05	11.87	8.85
		T7	630-744	616-626	567-612	.05	12.69	10.09
		T8	630-746	616-626	567-612	.06	16.68	12.24
T1	626-636		640-732	626-636	567-622	.32	>55.5	11.66
		T2	640-734	626-636	567-622	.32	39.45	12.78
		T3	640-732	626-636	567-622	1.12	18.35	12.24
		T5	670-744	656-666	638-652	.02	.48	9.93
		T6	640-745	626-636	567-622	.04	13.67	9.98
		T7	640-744	626-636	567-622	.04	13.88	10.82
		T8	640-746	626-636	567-622	.07	17.41	12.59
T1	696-732		na	696-732	567-692	9.25	na	1.54
		T2	696-734	682-696	567-678	9.15	2.84	1.43
		T3	696-732	682-692	567-678	.84	2.27	1.12
		T5	na	736-744	638-731	na	.80	.62
		T6	na	736-745	567-732	na	na	1.06
		T7	na	736-744	567-732	na	.07	1.03
		T8	na	736-746	567-732	na	.07	1.19
T6	736-745		na	736-745	567-692	na	.22	.04
		T1	na	696-732	567-692	na	.09	.01
		T2	696-734	682-696	567-732	.09	.19	.00
		T3	696-732	682-692	567-678	.09	.04	.00
		T5	na	736-744	638-731	na	.10	.02
		T7	na	736-744	567-732	na	.16	.03
		T8	na	736-746	567-732	na	.14	.00

data analysis. The bedding-plane parting at about 742 FANGVD29 terminates against permeable sand-and-gravel deposits between boreholes T5 and T3. It is likely that the sand-and-gravel deposits recharge the bedding-plane parting during the aquifer testing, lowering the amount of drawdown. However, data analysis involved techniques where a homogenous and isotropic aquifer of infinite extent was assumed. These assumptions likely resulted in an overestimation of the transmissivity of the bedding-plane parting.

A series of single-well, constant discharge aquifer tests was performed in 18 test intervals isolated by use of a packer assembly in boreholes B125GP, B126GP, and B127GP by monitoring drawdown during pre-sample purging. Kh estimates based on analyses using the method of Cooper and Jacob (1946) ranged from 0.035 to 37 ft/d. The highest Kh values typically were associated with tests done in the upper part of the aquifer, at the 660-ft parting, and at the 525-ft parting. These estimates of Kh typically were higher than those produced with slug testing and indicated no systematic correlation with the results of the slug testing. However, these tests were useful for identifying intervals of comparatively high and low permeability.

Tracer testing

A tracer test was conducted in conjunction with cross-hole GPR tomography at boreholes T1-T8 to determine flow pathways and hydraulic properties of the permeable vuggy interval between about 618 and 638 FANGVD29. The test consisted of pumping from the 628-638 FANGVD29 interval in borehole T6 while continuously injecting a 10,000 mg/L sodium-chloride tracer into this interval at borehole T2. GPR surveys were done between the T2-T8, T2-T7, and T3-T8 borehole pairs to monitor the tracer movement. Comparison of GPR tomograms performed before and at various times during the tracer test (fig. A11) indicates predominately horizontal tracer movement through the 628-638 FANGVD29 interval with a component of downward movement because of either tracer-density effects or in response to pumping in wells BMW4 and BMW6. Tracer movement through the inclined fracture at 699-709 FANGVD29 also is indicated by the tomography.

Although the tracer did not migrate the entire distance from the injection to the extraction borehole, the tomograph data allowed analysis of the rate of tracer movement that would not have been possible otherwise, including calculation of an effective porosity of 8.8 percent for the interval at 628-638 FANGVD29. This value is substantially lower than the mean porosity of 15 percent measured from a core sample collected at this altitude in well G115BD. The difference in the calculated porosity may be the result of differences in the scale of investigation (inches for the cores and tens of feet of the tracer test), and the differences between total and effective porosity.

Flow modeling

The USGS modular computer code MODFLOW (McDonald and Harbaugh, 1988) was used to simulate steady-state, ground-water flow in the 80-mi^2 Belvidere study area (Mills and others, 2002a) (fig. F12). The objective of numerical model simulation was, in part, to determine ground-water-flow direction and locations of discharge and pathways of contaminant movement. Principal locations of ground-water discharge within the study area include the Kishwaukee River, its tributaries, and local water-supply wells. Most discharge to wells is to the eight municipal wells in Belvidere (BMW2-BMW9); six of which are open, in part, to the Galena-Platteville aquifer (BMW2-BMW7).

The flow model consists of four layers that represent the glacial drift aquifer (layer 1), the Galena-Platteville aquifer (layer 2), the Glenwood semiconfining unit (layer 3), and the sandstone aquifers of the Cambrian-Ordovician aquifer system, including the St. Peter aquifer (layer 4). Four zones, representing hydrologically different parts of the glacial drift aquifer, were assigned to model layer 1. Uniform properties were assigned to the individual model layers (2-4) representing bedrock aquifers. Although the Galena-Platteville aquifer is known to be heterogeneous and anisotropic, data were not available for reliable zonation of hydraulic properties of the unit; the persistence of lateral or vertical trends in properties that have been identified is uncertain. Lateral flow boundaries in the glacial drift and bedrock aquifers were placed at distances where flow is expected to be unaffected by pumping from the Belvidere municipal wells. Water levels in the glacial drift aquifer (layer 1) and along the western boundary of the Cambrian-Ordovician aquifer system (layer 4) were specified on the basis of available data. Water levels along the eastern boundary of the Cambrian-Ordovician aquifer system (layer 4) were located along a regional ground-water divide (Visocky, 1993, 1997).

The model was calibrated to ground-water levels measured in July 1993. Ground-water discharge estimated from streamflows measured in the Kishwaukee River and adjusted to account for inflow from its tributaries and wastewater discharge, in September 2000, also was used for model calibration. Ground-water-withdrawal rates were applied for all wells reportedly producing more than 1 Mgal during 1993, including the seven operational municipal wells (BMW3-BMW9). About 80 percent of these supply wells are located in the city of Belvidere (fig. 30).

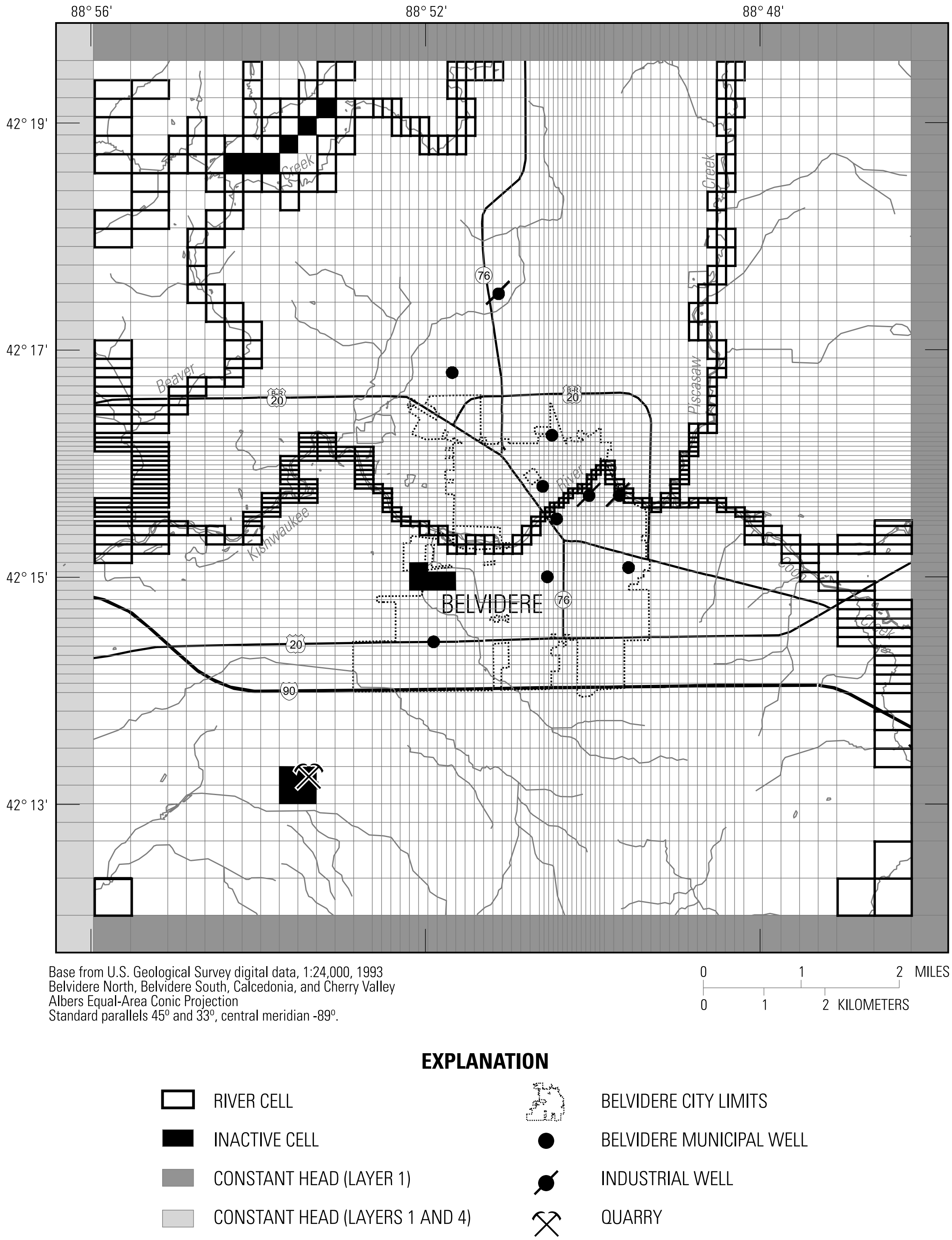


Figure F12. Model grid, boundary conditions, river cells, and wells used in the simulation of ground-water flow in the aquifers and confining unit underlying Belvidere, Ill.

A fundamental assumption made during MODFLOW simulation is that the hydrogeologic units represented by model layers are composed of continuous porous media. Although porosity that affects flow in the Galena-Platteville aquifer is represented predominantly by fractures and bedding-plane partings, these openings are connected; flow also occurs through vuggy intervals in the aquifer. Additionally, the smallest cell size, 250 ft by 250 ft, is substantially larger than the approximate 80 ft or less spacing between fractures (McGarry, 2000). Because of the cell size and the fracture spacing, the assumption of a continuous porous media is considered reasonable at the regional scale of flow simulation. Additionally, because of the higher permeability of the overlying and underlying aquifers, the model generally was insensitive to the hydraulic properties assigned to the Galena-Platteville aquifer.

Ground-water-flow paths simulated in a flow model can be delineated using particle tracking. By use of the USGS code MODPATH (Pollock, 1989) with output from MODFLOW, particle pathlines were computed in each model cell. Using the calibrated hydraulic conductivity and the computed three-dimensional hydraulic gradients, hypothetical water particles were tracked along the hydraulic gradient within the computed flow field (Mills and others, 2002b).

The particle-tracking scheme used in MODPATH is valid only for computing and interpolating advective velocities from intercellular flows. Accordingly, the particle pathlines are based on advective particle movement and travel times—no diffusion, dispersion, or chemical or microbiological retardation is incorporated into particle movement. The particle-tracking analysis was based on a model in which steady-state conditions are assumed and, thus, the analysis is insensitive to and does not represent short-term variations in natural (such as seasonal recharge) and anthropogenic (such as well withdrawals) stresses.

There is uncertainty in the simulated delineation of flow patterns and estimation of travel times by particle tracking. The calibrated model is a numerical representation of the ground-water-flow system; simulated water levels do not precisely match measured water levels, and actual ground-water-flow paths are more complex than the simulated flow paths. Numerical approximations, scale limitations, grid design, boundary conditions, and calibration data each can affect the accuracy of model simulation and, therefore, the particle-tracking analysis. Heterogeneity of the hydraulic properties of the aquifers underlying the study area, particularly hydraulic conductivity, is considered to have the greatest effect on the accuracy of this and other simulations of ground-water flow. Scale limitations of the numerical model also are considered to affect the simulation accuracy. Estimates of hydraulic conductivity can vary over as much as five orders of magnitude in the fractured dolomite of the Galena-Platteville aquifer. The initial model was designed to investigate regional ground-water flow. Local flow, such as flow to small streams and flow adjacent to sources and sinks, may not be represented accurately in the regional model. The model does not account accurately for the local effects of secondary porosity in the Galena-Platteville aquifer. Bedding-plane partings and inclined fractures are known to provide preferential pathways for water movement and seem to provide pathways for contaminant movement (Mills and others, 2002a).

For the model analysis, particles were forward tracked from the top and bottom center of all cells representing the glacial drift aquifer (layer 1) to determine where water discharges from the Galena-Platteville aquifer to the overlying glacial drift aquifer and from selected cells to determine flow paths from known or possible contaminant source areas to discharge locations. Because of the limitations associated with the scale of the regional model, including the inability to accurately define local hydrogeologic conditions, results of this analysis are considered most appropriate for general illustration of possible flow paths and discharge locations.

As part of the flow analysis, areas contributing recharge (ACR) to the Belvidere municipal wells and selected industrial wells also were delineated. ACR's to the wells open to the Cambrian-Ordovician aquifer system (model layers 2-4) were delineated by back-tracking particles from the full length of the interval of each well open to the Galena-Platteville aquifer (model layer 2) to the base of the glacial drift aquifer.

Given the hydrogeology and water quality in the vicinity of the supply wells, the approach used to delineate ACR's and ground-water travel times for the wells open, in part, to the Galena-Platteville aquifer is considered appropriate. In much of the area where the municipal wells are located, permeable deposits of sand and gravel (Kh up to 370 ft/d) that generally are less than 40 ft thick overlie the less permeable (Kh about 0.05 ft/d) Galena-Platteville aquifer (Mills and others, 2002a). These permeability contrasts contribute to rapid vertical movement of DNAPL's through the glacial drift aquifer and pooling on the surface of the dolomite aquifer; high concentrations of TCE (1,300 μg/L), indicative of nearby DNAPL's, have been detected within 5 ft of the top of the aquifer at the PCHSS (Mills, 1993b). DNAPL's, such as TCE and PCE detected in the aquifers underlying Belvidere, can move independently of the prevailing direction of ground-water flow in the aquifers because of the density contrast between the DNAPL's and ground water. As the DNAPL's dissolve in ground water, they can move from pool locations to area wells through a network of inclined fractures and subhorizontal bedding-plane partings, such as the network within the Galena-Platteville aquifer (Mills and others, 2002a). ACR's to wells for which such flow conditions are present cannot be simulated by conventional methods based solely on prevailing directions of ground-water flow.

In delineation of ACR's, errors in estimation of Kh result in substantial uncertainty in the representation of hydraulic gradients upgradient of a well (Varljen and Shafer, 1991) and, thus, errors in estimation of area-related ground-water travel times. Travel times also are affected by uncertainties associated with estimation of the aquifer porosity. Porosity has a linear effect on the travel time of a particle, but has no effect on the particle pathlines. An increase in the porosity decreases the area associated with each travel time. Porosities for the Belvidere model were estimated on the basis of literature values (Freeze and Cherry, 1979), laboratory measurements (Mills and others, 1998), and geophysical methods (Mills and others, 1998, appendix 6). Porosities of 20, 1, 1, and 25 percent were assigned to the glacial drift aquifer (model layer 1), the Galena-Platteville aquifer (model layer 2), the Glenwood confining unit (model layer 3), and the sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4), respectively. With possible under-estimation of porosity of up to one order of magnitude, travel times in the Galena-Platteville similarly may be under-estimated.

As indicated by the general simulation of flow (Mills and others, 2002a), about 90 percent of recharge is to the aquifers overlying the Glenwood confining unit, with most of the flow discharging through the glacial drift aquifer to the Kishwaukee River and its tributaries. Simulated potentiometric levels and flow directions approximate the levels and directions determined by synoptic measurements in 1993. The root-mean-square error between simulated and measured water levels was about 10 ft, with the majority of the error associated with levels in the deep sandstone aquifer system (model layer 4). Most of the discharge from the Galena-Platteville to the glacial drift aquifer occurs in the southern part of the Troy Bedrock Valley (fig. F13). About 65 percent of the flow entering the valley through the Galena-Platteville aquifer discharges to the Kishwaukee River and about 35 percent flows westward out of the study area. Only about 10 percent of recharge from precipitation (about 0.95 in/yr) flows from overlying aquifers to the St. Peter and deeper sandstone aquifers, also presumably within the southern part of the Troy Bedrock Valley, where the Glenwood confining unit seems to be partly to completely absent. About 7 percent of outflow from the ground-water system is discharge to the municipal and industrial wells in the area, less than 2 percent of this outflow is from the Galena-Platteville aquifer.

The Kh of the Galena-Platteville aquifer estimated from flow simulation was about one order of magnitude less than the Kh estimated based from the geometric mean of all available aquifer tests (0.05 ft/d and 0.59 ft/d, respectively). The difference indicates that the hydraulic conductivity of the aquifer may be substantially less in parts of the study area other than the city of Belvidere (where all of the aquifer tests were done). This difference may be attributed to a reduction in matrix and (or) fracture permeability.

The following characteristics of steady-state, ground-water flow in the Belvidere area are indicated from the simulated pathlines from possible contaminant source areas (fig. F14):

- Ground water moves from the glacial drift aquifer into the Galena-Platteville and underlying sandstone aquifers, particularly where flow is affected by withdrawals from the Belvidere municipal wells.

- Ground water discharges to three municipal wells (BMW3, BMW4, and BMW6; fig. F14), in part, through the Galena-Platteville aquifer.

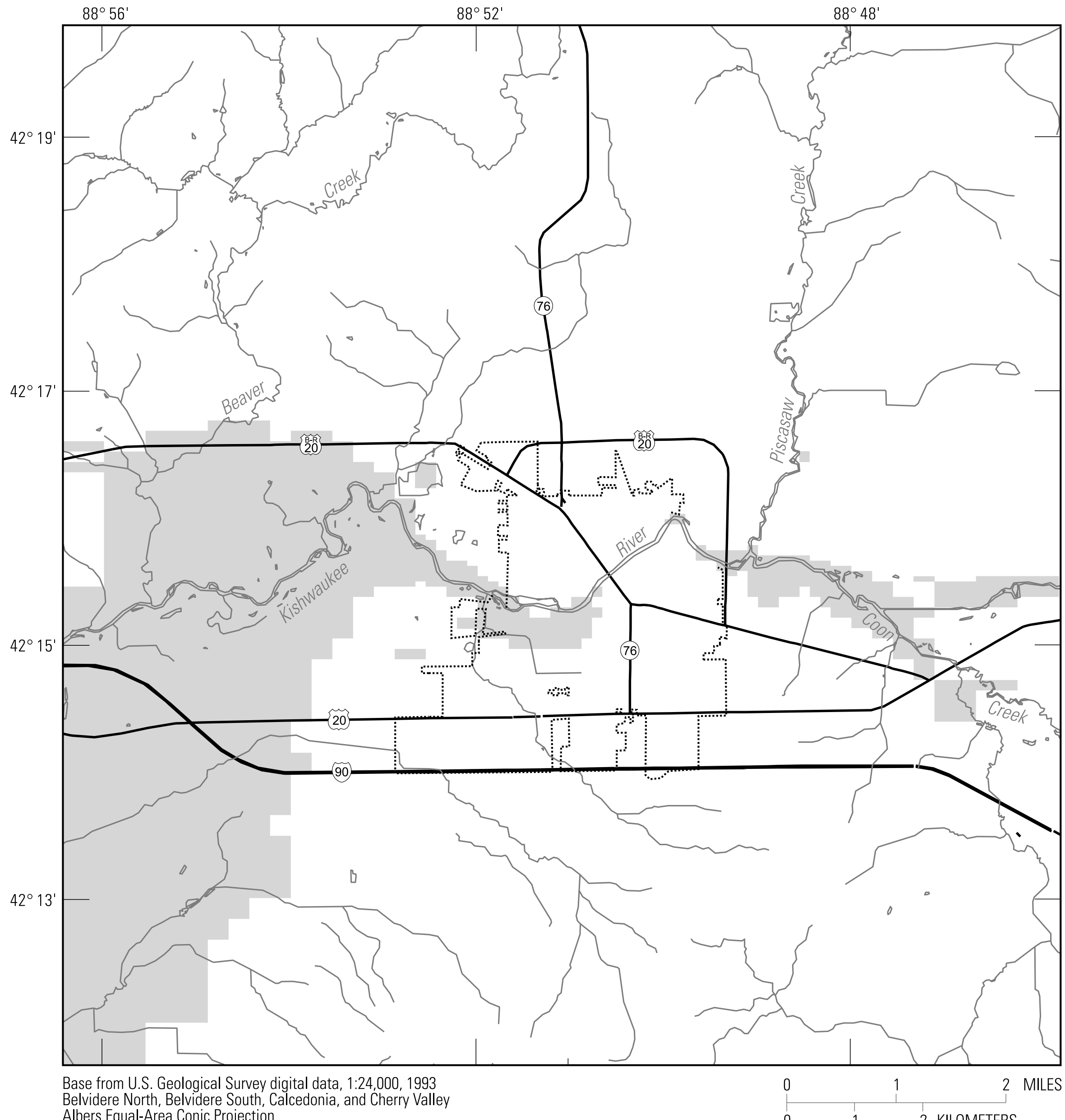
- Ground-water flow from one source area is northward beneath the Kishwaukee River in the Galena-Platteville and sandstone aquifers, with discharge to a municipal well (BMW4). Flow southward from the PCHSS and nearby source areas does not underflow the Kishwaukee River in the underlying bedrock aquifers. Apparently, flow into the bedrock aquifers near these source areas is affected more by pumping from nearby municipal wells (BMW4, BMW6) than by pumping from wells south of the river.

Ground-water flow that originates in the glacial drift aquifer may discharge to municipal well BMW8, a well open exclusively to the St. Peter and deeper sandstone aquifers underlying the Glenwood confining unit. On the basis of tritium data, near-well geology, and historical water-quality data, the St. Peter aquifer is considered to be confined and, thus, less vulnerable to contamination from overlying aquifers (Mills and others, 2002a, b). Flow simulation indicates that leakage through the confining unit represents only a fraction of total flow within the ground-water system simulated by the model. Thus, substantial contaminant transport to the St. Peter and deeper aquifers is considered unlikely.

During the 1993 model-calibration period, well BMW2 was not operating and well BMW3 was used sparingly. Total withdrawals for the municipal system were greater after 1996, when these wells were returned to full operation (J.A. Grimes, Belvidere Water Department, written commun., 2001).

The following characteristics of steady-state, ground-water flow in the Belvidere area, under ground-water-withdrawal rates of 2000 are indicated from the simulated pathlines from possible contaminant source areas:

- Underflow beneath the Kishwaukee River is restricted to the sandstone aquifers that underlie



Base from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard parallels 45° and 33°, central meridian -89°.

EXPLANATION

DOWNWARD DISCHARGE FROM THE GLACIAL DRIFT AQUIFER (MODEL LAYER 1) TO THE GALENA-PLATTEVILLE AQUIFER (MODEL LAYER 2)

UPWARD DISCHARGE FROM THE GALENA-PLATTEVILLE AQUIFER (MODEL LAYER 2) TO THE GLACIAL DRIFT AQUIFER (MODEL LAYER 1)

BELVIDERE CITY LIMITS

Figure F13. Simulated distribution of leakage from the Galena-Platteville to the glacial drift aquifer in the vicinity of Belvidere, Ill., 1993.

the Galena-Platteville aquifer.

- Some of the flow that discharged into the Kishwaukee River from source areas east and west of Belvidere in 1993 is diverted through the Galena-Platteville aquifer into the underlying sandstone aquifers. This flow discharges to municipal wells located almost 2 mi from the two contaminant-source areas.

Ground-water-flow patterns, as simulated by particle tracking, generally are substantiated by available water-quality data. Contaminant plumes have been mapped from many of the identified source areas, including the Parson's, MIG/DeWane, and Belvidere Landfill No. 1 Superfund sites (fig. 30). VOC's, particularly TCE and PCE, have been detected consistently in samples from wells BMW2 and BMW3, and intermittently in samples from wells BMW4 and BMW6 (Mills and others 1999, 2002a, b; Mills and Kay, 2003). However, flow paths

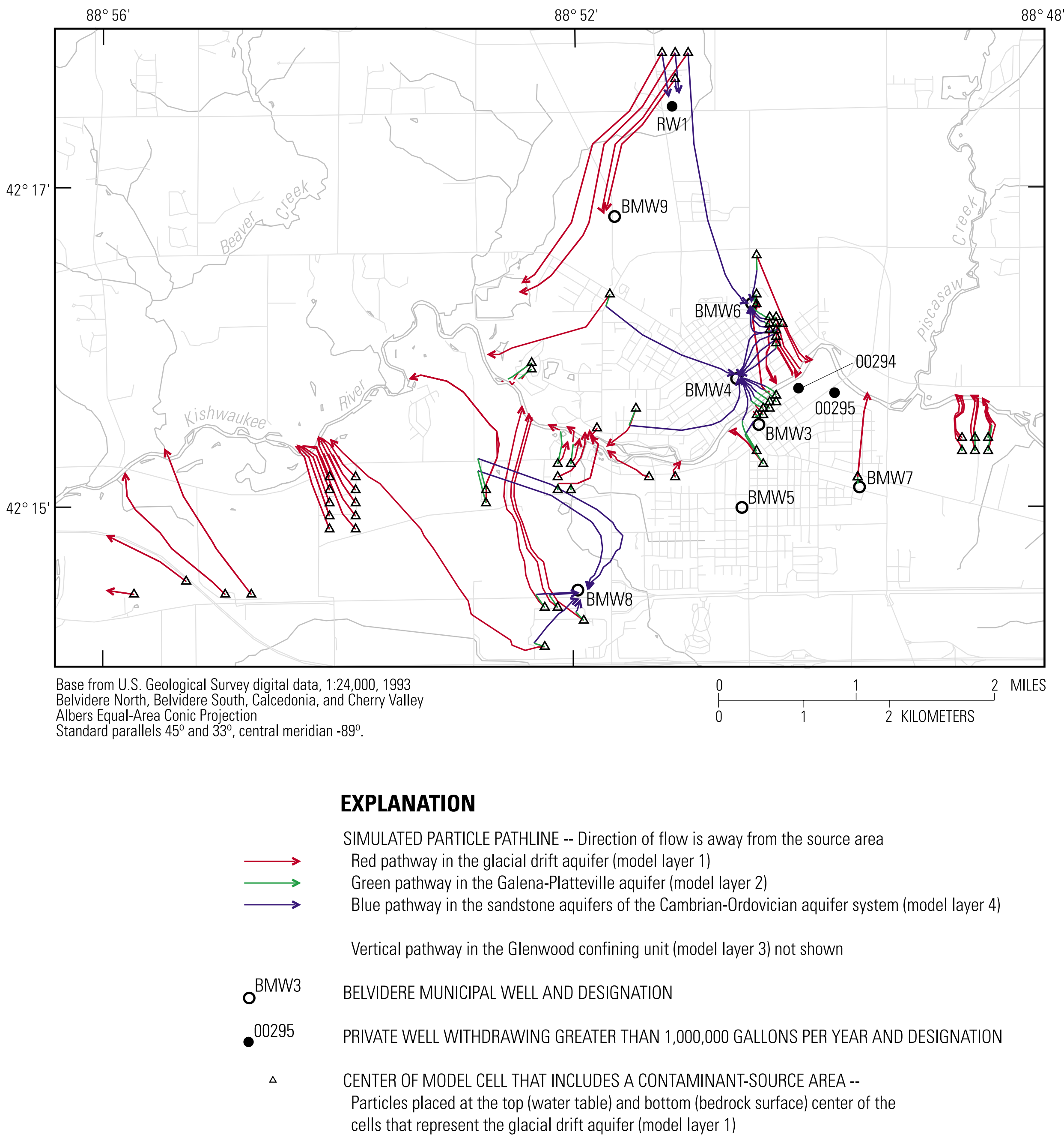


Figure F14. Simulated particle pathlines from possible contaminant source areas to discharge locations in the vicinity of Belvidere, Ill., 1993.

from some source areas may not be well delineated with the particle-tracking analysis because of insufficient representation of preferential flow paths. For example, the simulated pathlines for ground-water-withdrawal rates in 2000 indicate that ground-water flow in bedrock aquifers beneath the Kishwaukee River is restricted to the St. Peter and deeper sandstone aquifers. Sampling of isolated bedding-plane partings in the Galena-Platteville aquifer at borehole B137GP (fig. 30) in 2002 indicated VOC's that seem to be moving beneath the river from the PCHSS in the 525-ft parting and, possibly, other partings.

Areas contributing recharge to Belvidere municipal wells BMW3-BMW7 and industrial wells open to the Galena-Platteville aquifer are indicated in figure F15; areas indicated are not limited by travel time. The areas were simulated using the 1993 ground-water-withdrawal rates used for model calibration.

Ground water withdrawn from the Galena-Platteville aquifer is a mixture of waters with a range of residence times in the aquifer (fig. F16). Residence time in the aquifer is a surrogate for contaminant travel time because the simulation represents dissolved DNAPL's introduced to ground water near the top of the aquifer. The residence time for water that enters near the top of the aquifer is less than a year; the longest residence times are for water that enters a well near the base of the aquifer. For example, on the basis of an effective porosity of 1 percent, simulated residence times for water that is withdrawn from the Galena-Platteville aquifer by municipal well BMW3 range from about 0 to about 85 years with an average residence time of about 40 years.

Simulated residence times increase as porosity increases. Residence times for 50 percent of the water withdrawn from the Galena-Platteville aquifer, using porosity estimates of 1 and 20 percent, are contrasted in figure F16b. This porosity contrast is important, because of the uncertainty associated with estimating the effective porosity of the aquifer. Using the conservative estimate of 1 percent porosity, average residence times range from about 2 to 70 years. The shortest residence time is associated with a well that is open to only 22.5 ft of the aquifer and is located at the edge of the Troy Bedrock Valley, where the aquifer is only about 40 ft thick. The longest residence time is associated with a well with one of the lowest withdrawals rates included in the simulation and one of the longest open intervals in the Galena-Platteville aquifer (257 ft).

If the movement of ground water (and possibly contaminants) from near land surface to the top of the Galena-Platteville aquifer is rapid then the simulation-based estimates of residence times of water within the Galena-Platteville aquifer (model layer 2) can be compared reasonably to water-quality-based estimates of travel times of water from near land surface to various depths within the aquifer. Detection of methyl tertiary-butyl ether (MTBE) in water samples from municipal well BMW4 (Richard Cobb, Illinois Environmental Protection Agency, written commun., 2001), open to the deeper half of the Galena-Platteville aquifer, indicates that in this part of the study area, travel times between near land surface and the mid-part of the Galena-Platteville aquifer may be less than about 16 years (MTBE was first used as a gasoline additive in the United States in 1979). Tritium levels in samples from area wells open to the Galena-Platteville aquifer indicate that water withdrawn from almost all parts of the aquifer is less than 50 years old. These ages compare favorably with the residence times simulated for 50 percent of water pumped from the Galena-Platteville aquifer by the municipal and private wells, based on a porosity estimate of 1 percent (fig. F16B).

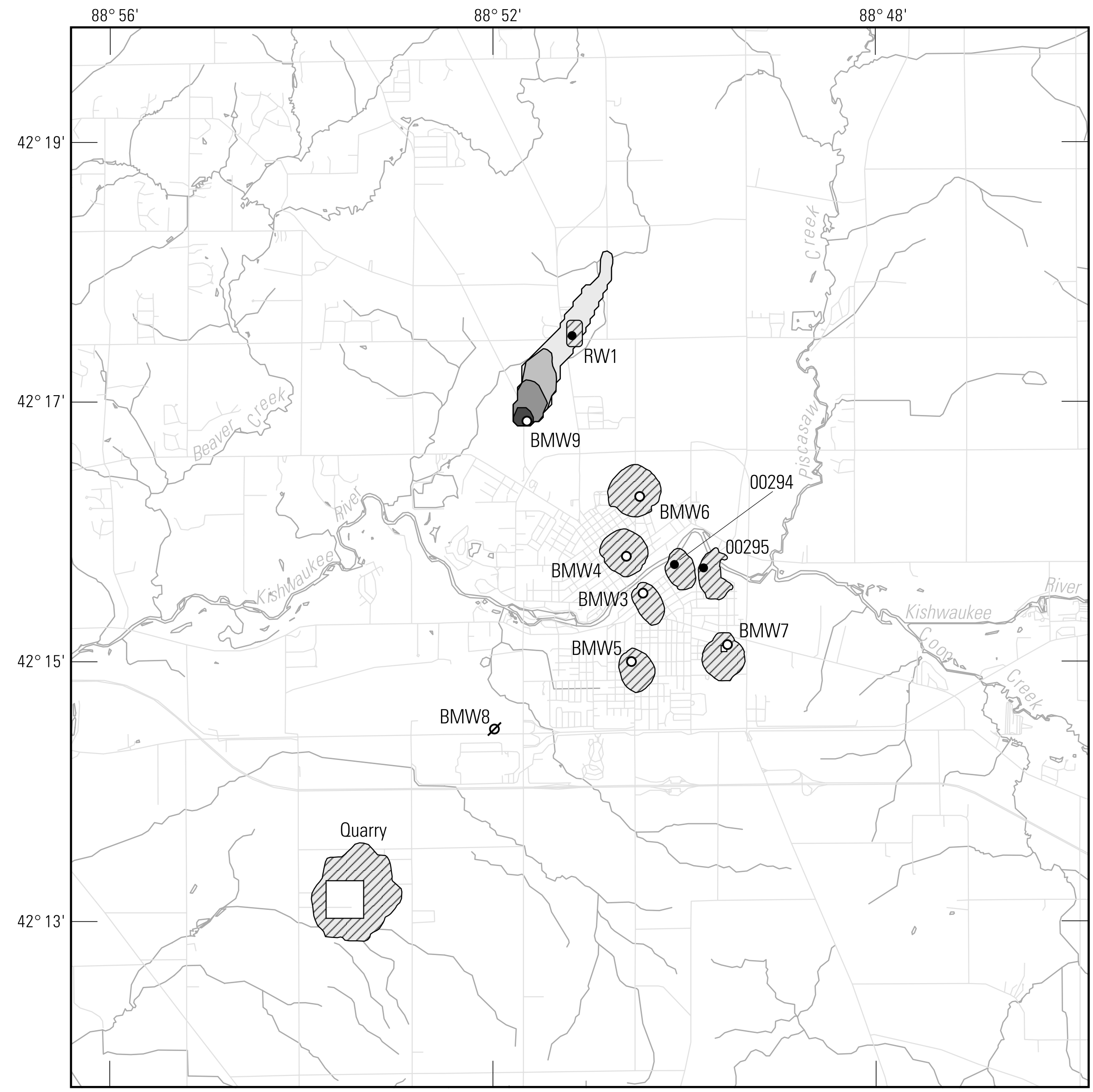
The effects of hydraulic-property heterogeneity and scale limitations on the accuracy of the model simulation of ground-water flow underlying the Belvidere area are mitigated to a large extent in that most of the hydraulic conductivity and porosity data were collected in the same part of the study area (in Belvidere) where water-level data were concentrated for model calibration, model-cell sizes were smallest, and particle-tracking analysis was focused. Although the uncertainties and limitations associated with this and other numerical models should not be ignored, such models provide unique and important understanding of ground-water-flow systems.

Locations of contaminants and other water-quality indicators

Water-quality data were collected from residential-supply wells, industrial- and municipal-supply wells, monitoring wells, and from test intervals in boreholes isolated with a packer assembly at various times from a variety of locations in the Belvidere area. Samples were analyzed for a variety of constituents, including VOC's, tritium, field parameters, and metals.

Synoptic and Periodic Sampling for VOCs in Water-Supply Wells

The concentration and distribution of VOC's in ground water beneath the Belvidere area was determined from samples collected from monitoring and water-supply wells, including the eight municipal wells in Belvidere (table 17) during a synoptic assessment of water quality performed during July 1993. Samples were collected from 60 wells open to the glacial drift aquifer, 30 wells (80 percent of available wells) open to the Galena-Platteville aquifer, and 4 wells open to the St. Peter aquifer (Mills and others, 1999). Samples also were collected from 15 wells open, in part, to the Galena-



Base from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard parallels 45° and 33°, central meridian -89°.

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

AREA CONTRIBUTING RECHARGE TO OPEN INTERVAL OF WELL IN GLACIAL DRIFT AQUIFER --
- 0-1 year
- Greater than 1-5 years
- Greater than 5-10 years
- Greater than 10-25 years

AREA CONTRIBUTING RECHARGE TO OPEN INTERVAL OF WELL IN GALENA-PLATTEVILLE AQUIFER FROM BASE OF GLACIAL DRIFT AQUIFER -- Maximum estimated travel times range from 2 to 67 years

BMW3 BELVIDERE MUNICIPAL WELL AND DESIGNATION

00295 PRIVATE WATER-SUPPLY WELL WITHDRAWING GREATER THAN 1,000,000 GALLONS PER YEAR AND DESIGNATION

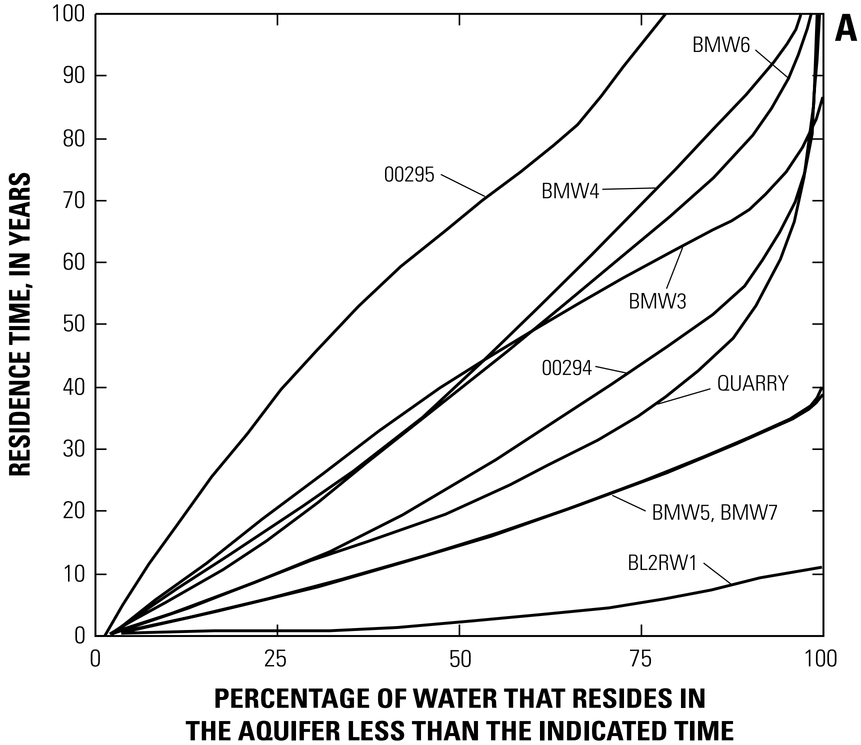
BMW8 BELVIDERE MUNICIPAL WELL OPEN TO CONFINED SANDSTONE AQUIFERS OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM AND DESIGNATION

Figure F15. Simulated travel-time-related areas contributing recharge to municipal and private wells withdrawing greater than 1,000,000 gallons per year in the vicinity of Belvidere, Ill., 1993.

Platteville aquifer, including 6 of the municipal-supply wells. During 1994-2002, samples were collected from about 25 wells open to the Galena-Platteville aquifer and 10 wells open to the adjacent aquifers; these data provided information on temporal trends in water quality in the Belvidere area (Mills and others, 1998, 2002a, b; Mills and Kay, 2003).

Sampling results indicate that VOC's are present in all aquifers underlying Belvidere, including the Galena-Platteville aquifer. Fine-grained sediments in the glacial drift seem to restrict distribution of metals and other inorganic contaminants to the immediate vicinity of the source areas. TCE and PCE are the principal VOC's detected at concentrations above regulatory levels (5 µg/L for these compounds), with the largest number of detections and highest concentrations in the glacial drift aquifer. Generally, VOC concentrations in the Galena-Platteville aquifer seem to exceed regulatory levels only at locations within about 0.25 mi of contaminant source areas, including the PCHSS. Across most of the study area, the Glenwood confining unit restricts downward movement of VOC's into the underlying St. Peter aquifer. In the vicinity of the Belvidere municipal-supply wells, downward movement also seems restricted by lateral movement of flow toward the municipal wells through permeable intervals (fractures, partings, and vugs) in the Galena-Platteville aquifer. Fractures and (or) unused wells that may penetrate the confining unit seem to provide local pathways to the sandstone aquifers. VOC concentrations in most wells varied little over the 9-year study period indicating a near steady-state, ground-water-flow system. However, near wells BMW2 and BMW3 (fig. 30), VOC concentrations in the Cambrian-Ordovician aquifer system, which includes the Galena-Platteville aquifer, and the overlying glacial drift aquifer, seem to be fluctuating in response to changes in the use of these municipal wells, which were not operating during about 1992-96.

The distribution of VOCs in the Galena-Platteville aquifer in the vicinity of the PCHSS indicates that the bulk of the VOC plume is migrating from the site, through the area of borehole B134GP, and toward the Kishwaukee River. Although this interpretation is complicated by the potential presence of source areas other than the PCHSS, the presence of VOCs in municipal wells BMW4 and BMW6 (Mills and others, 1999; 2002) as well as boreholes B124GP, B130GP, B133GP, B136GP, and B137GP, indicates flow components in the aquifer to the north, east, and west, and beneath the river to the south. The bedding-plane parting at about 525 FANGVD29 appears to be a primary conduit for flow in the aquifer. This interpretation is consistent with the analysis of the



B

Well	Porosity, in percent: 1	Porosity, in percent: 20
RW1	2	50
BMW6	40	800
BMW4	40	800
00294	20	500
00295	70	1,000
BMW3	40	800
BMW7	10	300
BMW5	10	300
QUARRY	20	400

Residence time of 50 percent of the water, in years

Figure F16. Simulated residence time of water in the Galena-Platteville aquifer (model layer 2) withdrawn by selected wells in the vicinity of Belvidere, Ill., (A) distribution of residence times using a porosity of 1 percent and (B) residence times of 50 percent of the water using porosities of 1 and 20 percent.

continuous water-level measurements from the deeper parts of the aquifer, but was not apparent readily from the single water-level measurements.

Tritium Sampling

Tritium samples were collected from six wells open exclusively to the Galena-Platteville aquifer and eight wells open exclusively to the adjacent aquifers (Mills and others, 2002a, b). Tritium levels above 1 TU in all samples indicate water throughout the Galena-Platteville aquifer was derived from recharge that occurred within the past 50 years (fig. F17). The aquifer is considered unconfined (Illinois Environmental Protection Agency, 2003; Szabo and others, 1996), with at least moderate vertical hydraulic connection. Tritium concentrations indicated no clear trends with depth, reducing the utility of this method for identifying flow rates or providing a narrower range of ground-water ages within the aquifer.

Sampling from Test Intervals Isolated with a Packer Assembly

The distribution and concentration of VOC's in ground water beneath the Belvidere area also was determined by sampling specific depth intervals at 14 monitoring wells and 8 boreholes at test intervals isolated with a packer assembly; sample locations were within the limits of the city of Belvidere, primarily in the vicinity of the PCHSS (Mills and others, 1998, 2002a, b; Mills and Kay, 2003). Vertical profiling was used to identify pathways for preferential flow through the aquifer.

VOC's are present throughout the aquifer, indicating ground-water flow and contaminant migration through a hydraulically connected network of inclined fractures, bedding-plane partings, and vugs. The generally widespread distribution of VOC's within the aquifer precludes identification of specific flow pathways in most of the aquifer. However, VOC's were detected only in the test interval open to the 525-ft parting in borehole B137GP, indicating that this parting is a flow pathway.

Sampling of specific depth intervals in wells and boreholes provided useful information on vertical directions of flow and distribution of contaminants in the Galena-Platteville aquifer, particularly in an area affected by pumping from municipal wells. Movement of water was indicated to be downward, with VOC's distributed through most of the 300-ft thickness of the aquifer beneath the PCHSS. Concentrations of VOC's in the test intervals isolated with a packer assembly displayed no clear and direct correlation with aquifer permeability (fig. F18). However, VOC concentrations typically tended to be highest in the upper 10-20 ft of the aquifer, decrease in the intermediate intervals, and increase in the deepest intervals. The higher concentrations in the upper part of the aquifer appear to be related to the proximity of the contaminant source area(s) near the land surface.

The effects of vertical flow within the borehole on sampling results complicate analysis of water-quality data from test intervals isolated with a packer assembly. Common practices of purging the water from packer-test intervals using borehole-volume and field-characteristic stabilization criteria (Mills and others, 1998) may not adequately remove the artificially introduced water and, thus, may not provide representative samples from the aquifer. This possibility is supported by results of a field test conducted at borehole T5, in which water samples were collected for VOC analysis from four packer-isolated permeable intervals during drilling, immediately following drilling, and about 1 month after drilling.

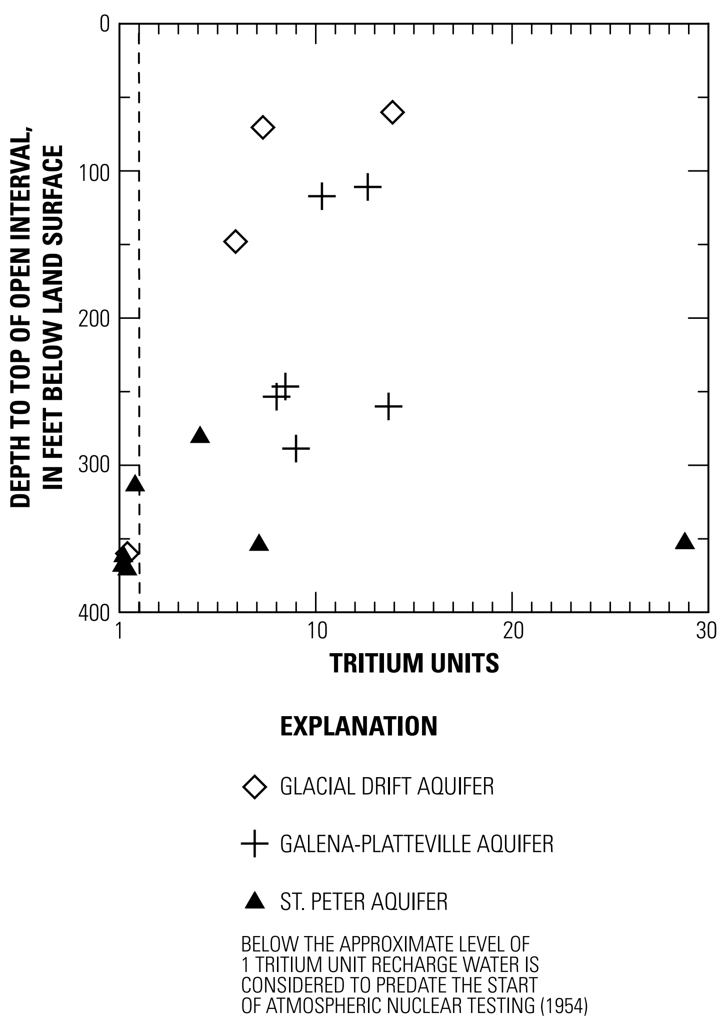


Figure F17. Tritium levels in aquifers underlying Belvidere, Ill., 1999-2000.

VOC concentrations in the samples near the bottom of the borehole increased by about one order of magnitude in 36 hours, indicating that the most representative packer-test results are obtained as soon as possible after drilling and adequate borehole development.

Analysis of the concentrations of naturally occurring water-quality constituents in the Galena-Platteville aquifer provided limited additional insight into the hydrogeologic characteristics of the aquifer. Notable exceptions were the analyses of arsenic, chromium, cobalt, and fluoride concentrations with depth in borehole B127GP (Mills, 1993b). Arsenic, chromium, and cobalt were present at detectable concentrations only in the test intervals open to the permeable subhorizontal bedding-plane partings at about 485 and 525 FANGVD29. Also, concentrations of fluoride that generally were less than 0.3 mg/L increased to 1.8 mg/L in the test interval that included the 525-ft parting. These patterns indicate that water quality in these intervals differs from that in the rest of the aquifer, either because of proximity to a naturally occurring source of these constituents, or because of preferential flow from a surficial source of these constituents into these bedding-plane partings.

Near-Continuous Vertical Profiling of Field Parameters

Field parameters were monitored in well BMW2 by in-situ, near-continuous vertical profiling with a multiparameter, water-quality monitor (Mills and others, 1998) (fig. F19). In well BMW2, values of dissolved oxygen (DO), oxidation-reduction potential (ORP), pH,

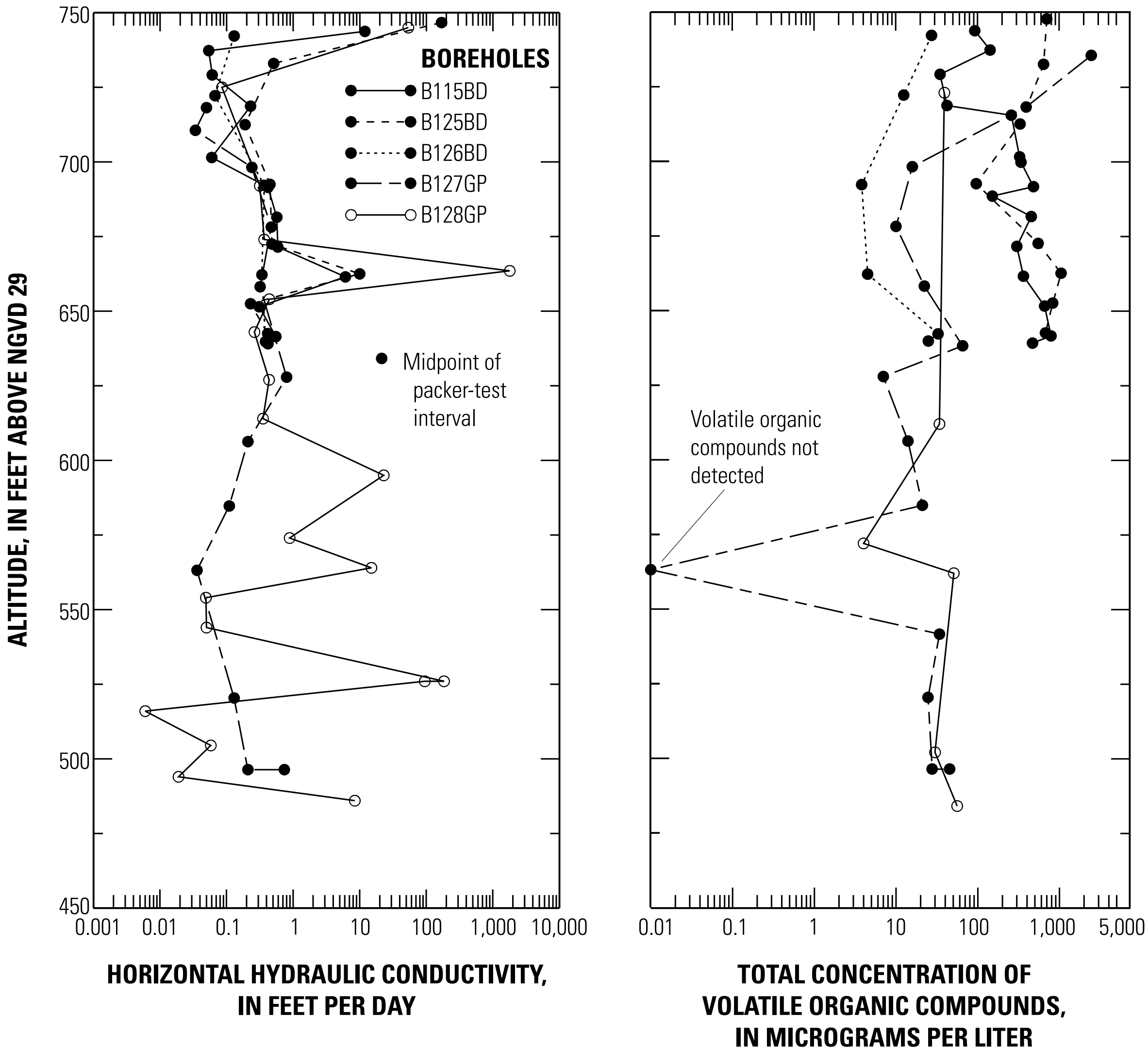


Figure F18. Vertical distribution of horizontal hydraulic conductivity and total concentration of volatile organic compounds at select boreholes open to the Galena-Platteville aquifer underlying Belvidere, Ill.

specific conductance, and temperature generally were more variable (either increasing or decreasing) above 675 FANGVD29 than below. The vertical trends in concentrations of DO and ORP generally mirrored each other. With the exception of temperature, all other paramaters fluctuated (increased or decreased) between the altitudes of about 680 and 635 FANGVD29. The fluctuations may be indicative of inflow of water from the 660-parting and the inclined fracture identified at about 625 FANGVD29 in the caliper and acoustic-televiewer logs. In-situ profiling of water quality was not done at depths below 200 ft because of instrument limitations. The observed trends seem to represent (1) flow-induced mixing of waters of the glacial drift aquifer and the shallower part of Galena-Platteville aquifer, (2) atmospheric effects on water characteristics near (within about 60 ft) the water surface, and (or) (3) mechanical mixing of water in the well with movement of the profiling monitor.

Profiles of DO, ORP, pH, specific conductance, and temperature by use of the multi-parameter water-quality monitor in borehole B127GP (fig. F19) generally were more variable (either increasing or decreasing) above than below 682 FANGVD29. These data indicate mixing of different waters above 682 FANGVD29, and the presence of more variable flow above 682 FANGVD29 than below this altitude. An increase in ORP and decreases in temperature and pH at and below about 524 FANGVD29 indicate possible inflow of water from the bedding-plane parting at this altitude.

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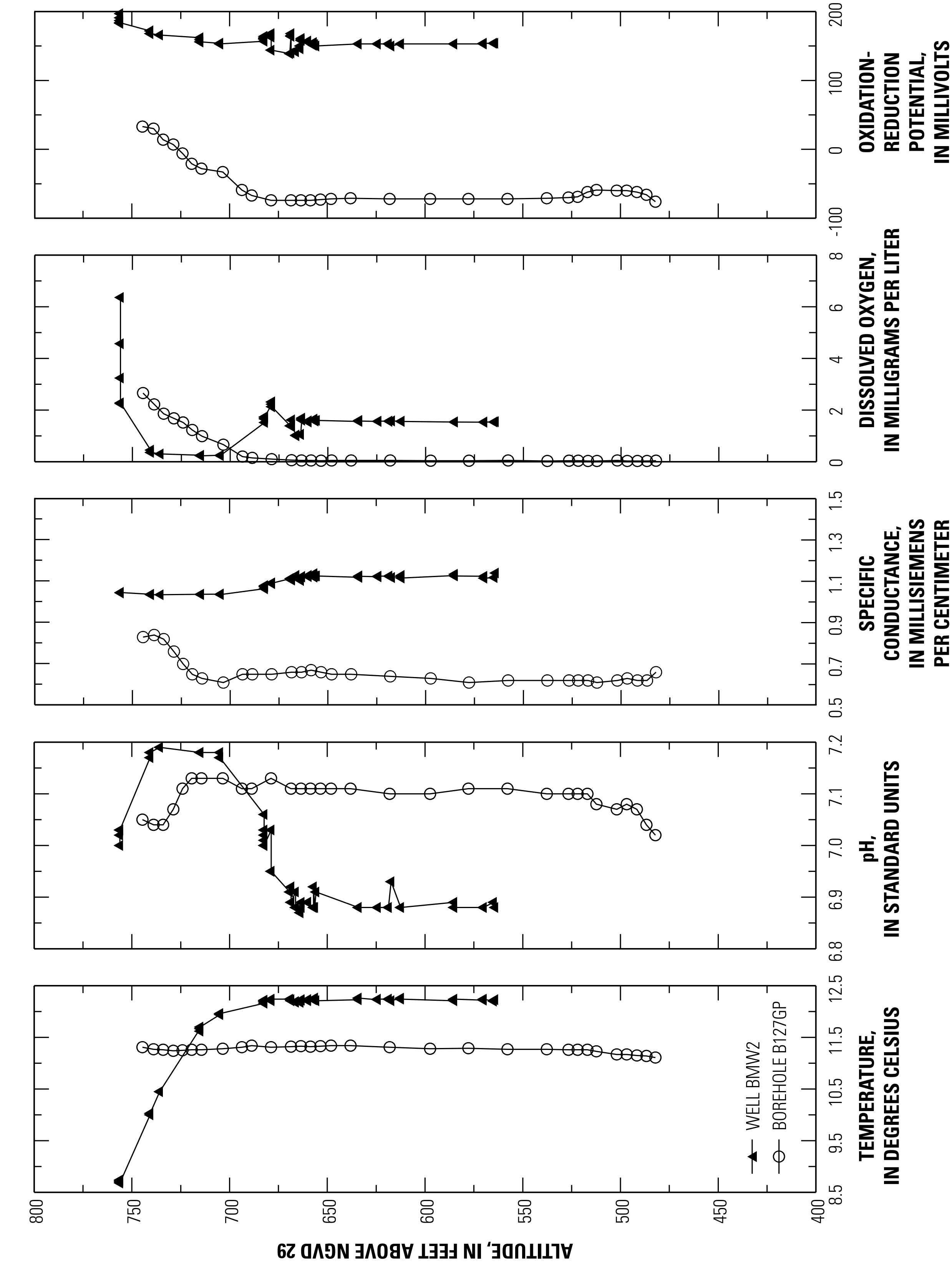

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